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Telephone Switchboard at Georgetown, British Guiana

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CONTENTS

Page

142 Frontispiece—An RW 300 Digital Control Computer at the B. F. Goodrich Chemical Company plant in Calvert City, Kentucky

143 Computers for Industrial Production-control and Optimization
By E. M. Grabbe

148 Microminiaturization
By G. W. Edwards

155 Highly Stressed 132 kV Oil-filled Cable installed at Melksham
By E. H. Ball

160 High-frequency Germanium Transistors
By B. A. I. Davis

165 Progress in Research on High-pressure Mercury Vapour Lamps
By E. H. Nelson

172 Generation and Amplification in the Millimetre Wave Field
By W. E. Willshaw

182 Technical Literature

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COVER PICTURE

The auto-manual telephone switchboard at Georgetown, British Guiana. This 12-position switchboard is part of the 5200-line automatic telephone exchange manufactured and installed by The General Electric Co. Ltd. of England for the Ministry of Communications and Public Works.

An RW 300 digital control computer at the B. F. Goodrich Chemical Company plant in Calvert City, Kentucky, controls and monitors two distinct chemical processes—one producing material used in vinyl plastics and the other producing ingredients for special-purpose rubber compounds.

Computers for Industrial Production-control and Optimization

By E. M. GRABBE, Ph.D., M.Sc., International Systems Control Ltd.

INTRODUCTION.

ON 26 June, 1961, International Systems Control Ltd was formed to apply computers to optimize and control processes in industry. The company is a joint venture of the General Electric Company Limited and Thompson Ramo Wooldridge Inc. of the U.S.A., with the capital equally shared. The company will engineer and supply analogue and digital equipment for the control of industrial processes in the United Kingdom, the Commonwealth and the countries now in the Free Trade Area. It will have the advantage of the experience of T.R.W. in process-control on the one hand, with the engineering resources and contacts of the G.E.C. on the other.

The advent of digital control systems is the latest development in automation. First came (*a*) devices to do work, then (*b*) measuring and controlling devices, and finally (*c*) computing devices. The third phase of this development means a shift in emphasis from the components and equipment for a process to the system as a whole and the information available about it. The trend is now to study the process with the object of ascertaining the mathematical relations between the factors which determine the economic performance and behaviour of the process. These relations can then be used to control production in an optimum manner.

Industry is always striving to increase production, reduce costs and improve quality. As the demand for products has steadily increased, industry has increased in size and complexity and has developed faster and more intricate processes. At present human operators monitor these plants and periodically adjust the controllers according to charts, graphs, and rules based upon past experience. The procedure usually involves a considerable time-lag and the manager generally demands a safety margin. The result is production at considerably below optimum. In plants where the overall performance is limited by the capacity of the operators in this way, electronic digital computers may be placed in the control loop to handle high-speed computations, make decisions and control actions.

Digital computers have proved themselves in scientific and engineering computing and in business data processing. In the latest applications to industrial process control and monitoring systems, the computer occupies an ' on-line ' (also called in-line or real-time) position in that it is connected directly to many measuring instruments of the process (fig. 1).

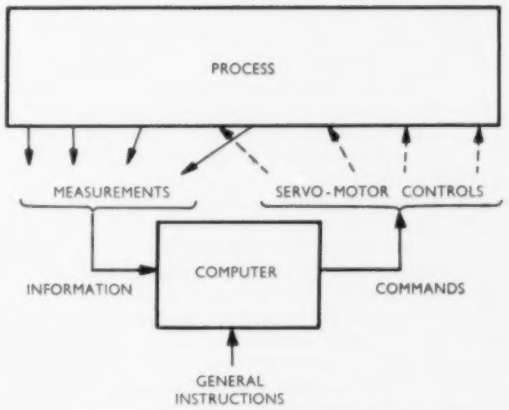

Fig. 1.—The computer in the control loop.

COMPUTER CONTROL.

The use of computer control to optimize production is extending rapidly. The RW 300 digital control computer was the first machine to be designed and introduced for controlling industrial production processes. The group at Thompson Ramo Wooldridge which designs these process control computers had a long history of experience in the design of computers for aircraft and missile control before turning to industrial computers.

The first closed-loop installation of a control computer[1] was an RW 300 at the Texaco catalytic polymerization plant at Port Arthur, Texas (fig. 2). Other applications include electric power, nuclear power, steel, chemical, petroleum, minerals, testing, pipelines, aircraft and missile industries. In most of these industries the RW computers were the first to be

employed, hence Thompson Ramo Wooldridge has developed a broad background of experience. The possible range of uses appears to be almost unlimited. International Systems Control will draw on all this experience.

Many industrial processes have already a degree of local control by means of measuring instruments linked to a controller whose ' set-point ' is adjusted by the operator.

The heart of a digital computer control system is a general purpose computer with a fixed programme. The computer communicates directly with process measuring instruments, it performs complex calculations on the input data on a moment-to-moment basis to determine the controller set-points for optimum operation, and automatically supplies the signals necessary to adjust the set-points of the controllers. The equipment involved in a typical installation is as follows:

(*a*) An RW digital control computer.
(*b*) The associated equipment which performs the analogue-to-digital and digital-to-analogue conversions and so enables a digital computer to interpret analogue signals from the process measurements and to put out analogue control signals.
(*c*) Switching relays, controls, and alarms for scanning inputs and outputs.
(*d*) Added automatic instrumentation, frequently of the continuous analyser type, for implementing feedback or feed-forward control loops.
(*e*) Transducers for converting pneumatic signals into electrical signals.

In addition to the equipment details, engineering studies are an important part of each system installation and will be discussed later.

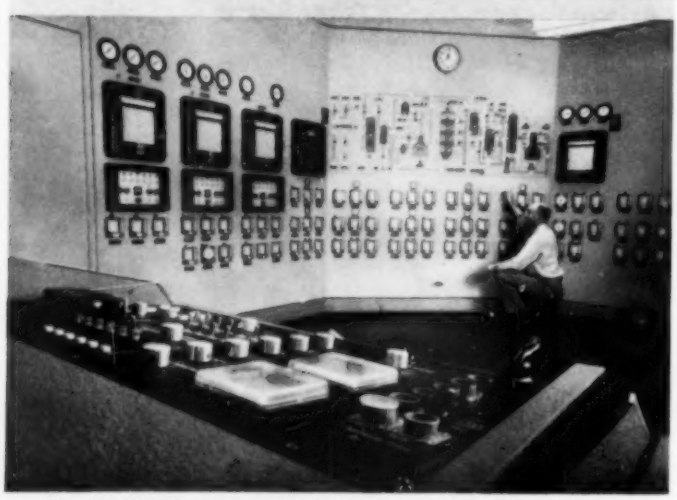

Fig. 2.—RW 300 computer in the instrument room of the Texaco catalytic polymerization plant at Port Arthur, Texas.

COMPUTER FUNCTIONS.

Computer control can be applied in a variety of fashions depending on the characteristics of the particular process. The control system may be designed to give any of the following fully automatic types of control; either singly, or in combination:

(1) Optimization of the performance of the process with respect to some specified criterion (e.g., fuel consumption, yield of product) using either (*a*) a mathematical model of the process or (*b*) an empirical technique for methodically searching step-by-step for an optimum.
(2) Feed-forward control with computed compensations for the independent variables of the process which can be measured, such as variations of load, changes in the compositions of the input material, disturbances, etc.
(3) Feedback control based on the performance of the process, computed from measured variables and measurements made by continuous analyser on the output of the process.
(4) Adaptive type control. In this the computer adjusts the mathematical model of the process to take into account slow changes in the behaviour of the plant.
(5) Refinement or building-up of a mathematical model based on automatic analysis of information from the process.
(6) Controlled start-up and shut-down of plants.

In addition to the automatic control functions listed, the control computer can carry out the following functions which have the nature of diagnosis or the processing of data.

(*a*) Monitoring (alarm scanning) and actuation of warnings and alarm signals with visual display or print-out.
(*b*) Accurate recording of process data with print-out as required.
(*c*) Statistical analysis, correlations, and other required computations for engineering, accounting and management control.
(*d*) Check and calibration of instruments.
(*e*) Detection and indication of failure of equipment or instrument.
(*f*) Anticipation and indication that maintenance or replacement is necessary.

PLANNING FOR COMPUTER CONTROL.

Detailed engineering studies are required to prepare the ground for an effective installation.[2] The selection of a process for computer control must be made both on technical and on economic grounds. From the technical standpoint there must be a certain minimum understanding of the process. Sufficient data on past operating

performance should be available so that, in the absence of a theoretical understanding, the necessary empirical relationships can be determined. On the basis of these, the control functions can be established, and a preliminary estimate of the expected gain can be made. A short preliminary study will usually be required to make this estimate.

Having selected a process which looks highly promising, a more detailed study is undertaken to determine the functions to be performed by the computer. These will include not only the control functions, but also data-logging, alarm activation, checking of process instruments and equipment for proper functioning, self-checking of the computer, etc. A careful analysis must be made of existing instrumentation and any new instrumentation that may be used to advantage in the computer control system.

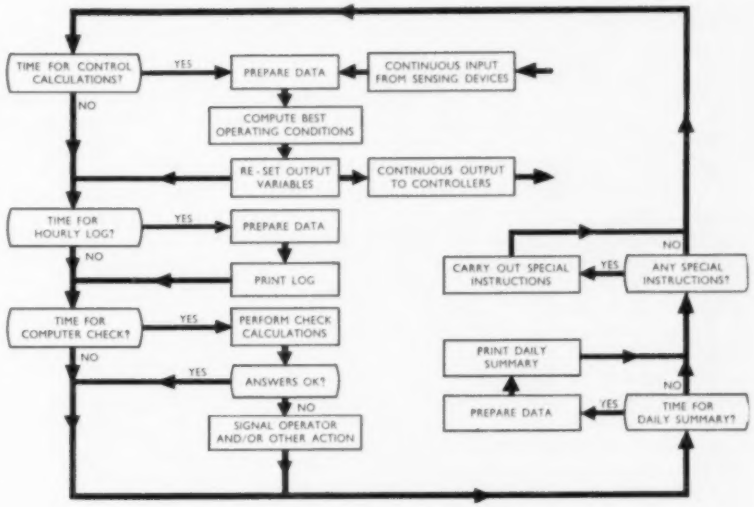

Fig. 3.—Typical operating programme.

A very important phase of the engineering study is establishing the relationship between the controlled variables, the disturbances of the process and the behaviour of the process. In general the controlled variables must be manipulated so as to compensate for disturbances in order to maintain stable and optimum control. This phase of the study also includes a critical analysis of a number of possible objectives, which may vary with market conditions or with the objectives of other process units associated with the unit under study.

A further requirement is to study the dynamics of the process, although a computer control system does not usually look after the dynamics of the process, since dynamics are handled by the individual loop-controllers which the computer control system supervises. It is, nevertheless, necessary to assure that no upset occurs if the computer controller takes rapid action. If such a danger exists, the computer can be programmed to make the controlling actions at a rate which will not cause upset.

Another important consideration in the study is assuring that a computer control system will always fail to safety. Even though computer reliability may be 99·9%, there must be absolutely no risk that a major upset of the process could occur at any time. All possible failures of the control system need to be examined and proper precautions taken to assure that in any of these contingencies the process would continue to operate safely.

The final phases of the study are concerned with making an estimate of the cost of equipment to exercise computer control over the process and a careful study and a final estimate of the potential pay-off that can be realized by using a computer control system.

The system engineering studies can be effectively carried out by a co-operative effort on the part of the customer and companies such as International Systems Control, which specialize in the systems engineering for digital computer control. Systems engineers are needed who have combined knowledge of the operation and instrumentation of processes, together with a knowledge of digital control technology. A joint study thus utilizes the customer's knowledge of his special process and acquaints the customer's engineers with the capabilities of the new technology enabling them to make their own evaluation of the benefits of computer control.

The study will lead to a detailed mathematical model for operating the control system in an optimum fashion. Then the plant is prepared for the installation, the computer programmed and the final phases of installation and operation are carried out. Fig. 3 illustrates a typical operating programme.

MATHEMATICAL MODELS.

In designing a computer control system for chemical and other industrial processes, four types of mathematical relationships between process variables are of importance. The final model which is continuously used by the computer for control will contain all of these relationships directly or indirectly. These are:

(1) A profit equation which expresses the economic objectives of the working of the process.

(2) Constraints or restrictions imposed upon the working of the process by factors such as the availability of materials, product quality, specifications, equipment ratings, safety requirements, etc. Usually these are in the form of inequalities.

(3) Relationships developed from fundamental physical and chemical principles including material

and energy balances, reaction kinetics, equilibrium relationships and properties of material. These relationships define the transfer functions for the process which relate the output behaviour to the changes in input variables and enable the computer to control the process in an optimum manner.

(4) Procedures which permit the model to adapt itself automatically to changes in the process.

An excellent compilation of typical models including material- and heat-balances, chemical reactions, catalyst deactivation, material transport, separation, and blending has been made by Stout.[3] *Static* or *steady-state* models do not depend on time and are expressed as algebraic equations. *Dynamic models* are in the form of differential equations of the process. Dynamic models have been determined by various techniques including step and frequency response, analogue computer simulation and correlations.

A steady-state model is a simplification of an associated dynamic model and can be developed without reference to the dynamic characteristics of the process. Ordinary process calculations are made in this manner, and much information is available which can be adapted to the needs of the designers of computer control systems.

OPTIMIZATION TECHNIQUES.

The major value of digital computer control system lies in its ability to optimize plant performance. If the performance p, to be optimized is expressed as a function of the process variable[4] illustrated in fig. 4, as follows:

(1) $p=f(u_i, m_j, q_k)$

where u_i = independent variables, $i=1, 2, 3, \ldots, I$

m_j = dependent variables, $j=1, 2, 3, \ldots, J$

q_k = system output or computed variables, $k=1, 2, 3, \ldots, K$

The system variables will be related by mathematical equations which can be written as:

(2) $g_l(u_i, m_j, q_k)=0,\ l=1, 2, 3, \ldots, L$

Some of these equations may be in the form of inequalities which impose constraints on the process; others are based on physical or chemical laws and on empirical relations.

The excess of variables over equations yields the number of degrees of freedom of the system. Since the independent variables are assumed to be measured directly, the number of degrees of freedom F are:

(3) $F=J+K-L$

For an optimum solution of equations (1) and (2), K of the L equations (2) may be used to eliminate q_k ($k=1, 2, 3, \ldots, K$) from equations (1) and (2). Then take partial derivatives of p with respect to F of the manipulated variables m_j.

(4) $\dfrac{\partial f}{\partial m_j} = 0,\ j=1, 2, 3, \ldots, F$

The F equations (4) and the remaining $L-K$ equations (2) are sufficient to determine the J unknowns (m_j) since $F+L-K=J$.

The methods of obtaining optimum solutions to these equations can be listed without detailed explanations. They include:

(1) Direct solution when an analytical model is available. For a large problem with many variables the equation can generally be simplified to reduce the number of variables.

(2) Lagrangian multipliers are useful when inequalities exist. Trial and error procedures are necessary for constraints with upper and lower bounds.

(3) Linear programming by Simplex method of solution.

(4) Calculus of variations has broad applications. Again trial and error techniques may be required.

(5) Dynamic programming formulates the problem as a series of distinct decision processes. This method may require large storage-capacity and long computing-time.

(6) Gradient method, a direct method of optimization without a mathematical model. The change in performance is evaluated in relation to the direction of step changes made by the computer in manipulated variables.

(7) Steepest descent method, a strategy to improve the exploration procedure when making step changes during direct optimization.

The choice of the method of optimization will depend on the knowledge of the process and the ability to describe it in analytical form. Any or a combination of the above methods may be used in a particular case.

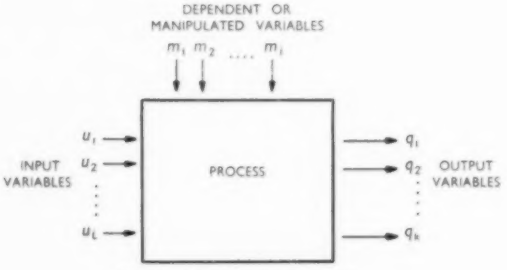

Fig. 4.—Variables in a process.

TYPICAL EXAMPLES.

Electric and Nuclear Power.

RW 300 computers already installed or on order will control close to 2000 megawatts of generating power in various parts of the world. This is more than the power controlled by all other process control computers in the power industry. The largest power generating plants in the U.S. which are being constructed for the Tennessee Valley Authority will employ RW 300's. The Electricité de France has six RW 300's installed or on order. The first application of computers to nuclear power[5] was made by Electricité de France using RW 300's (fig. 5). Another nuclear application

of RW process-control computers has been for experimental pile testing by the French Atomic Energy Commission. In France and the Common Market countries the manufacture and marketing of RW process control computers are carried out by Compagnie Europeanne d'Automatisme Electronique (CAE), a joint company of C.S.F. and T.R.W. There will be a close collaboration between C.A.E. and I.S.C.

THE FUTURE.

Most of the problems handled by industrial process control computers today involve steady-state or equilibrium conditions. This means that they can be described by algebraic equations which do not involve time. As more is learned about processes there will be a trend toward dynamic control. This means controlling a process on the basis of the time-dependent differential equations which govern its behaviour. We can look forward to sensational advances in process design based on experience with computer control and advanced knowledge of the process.

The computer cannot replace the human being, but it can relieve him of monotonous and routine calculations and work and perform them better and quicker, leaving him free for better tasks.

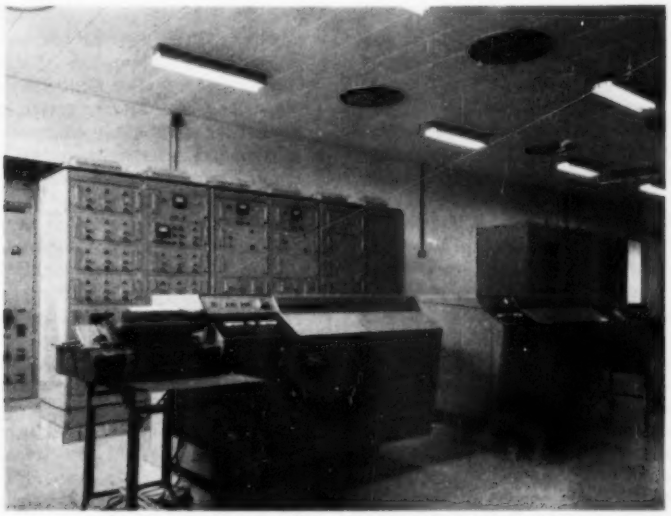

Fig. 5.—Installation at Chinon France for Electricité de France.

CHEMICAL AND PETROLEUM.

Among the applications which have been announced of T.R.W. computers in this field,[6,7] are Goodrich Chemical, who have a vinyl chloride plant; Texaco, catalytic polymerization; Monsanto, ammonia; Gulf, catalytic cracking, and many others.

STEEL.

The first application of a control computer to a 'tonnage-oxygen' steel process (LD type) is now under study with the Great Lakes Steel Company, and will employ an RW 300 computer.

MISCELLANEOUS.

Other applications of these computers include cement-making, missile-component testing, television broadcast switching, traffic control in the air and in cities and computation during weather reconnaissance flights.

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Microminiaturization

By G. W. EDWARDS, B.Sc., D.I.C., A.I.M.E.E., Hirst Research Centre.

INTRODUCTION.

THE desire to compress more components into a given space is not new and has existed, for one reason or another, ever since the first production of electronic equipment. It is only during recent years, however, with the rapidly increasing growth in complexity of both military and commercial electronic equipment, that this need has appeared as one of major importance to successful future development in these fields.

In spite of the rapid reduction in equipment size that has been made possible by the appearance of the transistor and the successful application of printed-circuit techniques, there is now a greater need than ever before for more compact designs of equipment to meet the requirements of the electronic systems of the future. Established techniques of circuit design and construction using these recent advances have in fact reached a limit of compression and a new overall concept is necessary if component densities much higher than those at present in use are to be obtained. At least an order of magnitude increase is required and for some applications even two or three orders of magnitude. A study of the ways of achieving such advances has now acquired an importance in its own right and has come to be known by the name of ' microminiaturization ' or ' microelectronics '.

This study has already been going on for some time, principally in America but also in this country, and much has already been written about the various approaches to which it has given rise. The present account is intended only as a summary of some of the main aspects of the problem as it stands at present and of the methods of approach that have been adopted.

It is worth saying at this point that a considerable vocabulary of descriptive names such as ' microcircuit ', ' integrated circuit ', ' composite circuit ', ' molecular electronics ', ' solid circuit ', etc., has already grown up around the different lines of development. Many of these are somewhat confusing since they are not always applied to the same concept, and conversely the same concept is often described by different names. Until there is more general agreement on nomenclature it is therefore necessary to give some interpretation of the meaning of the terms used. The interpretations used below have been chosen to be descriptive, rather than most generally accepted, and will therefore not necessarily be in agreement with similar terms used elsewhere.

The name ' microminiaturization ' itself is perhaps somewhat misleading in that it implies a certain size of resultant equipment or circuit whereas in fact it covers a large variety of methods of approach which lead to a range of component densities differing by 100 : 1 or more; this is about as great a range as already exists throughout all present electronic equipment. Microminiaturization is in fact just a continuation of the generic process of miniaturization but extending beyond the limits imposed by contemporary conventional methods.

The need for more compact equipment first started to make itself felt during the last war following the growth of airborne radar and navigational systems. The introduction of miniature-type thermionic valves in about 1944-5 enabled equipment with component densities up to about 2000-3000 per cubic foot to be produced. The subsequent introduction in the post-war period of a range of sub-miniature valves, largely to meet the requirements of weapon guidance systems, increased this figure to about 8000 components per ft^3. It was not however until the mid-1950's with the appearance of the transistor as an established production item that a major reduction in size could be made. In combination with the also newly-established production technique of printed wiring, transistor circuits were capable of achieving component densities up to about 50 000 per ft^3 and, although the use of especially small components, together with special methods of assembly and encapsulation, may enable this figure to be doubled, it appears to represent a limit to what can be achieved with the conventional circuit construction.

It is from this point that microminiaturization starts and the minimum aim has been to produce circuits and equipments with component densities of at least 500 000 per ft^3.

THE NEED FOR MICROMINIATURIZATION.

Although a major aim of microminiaturization is clearly the reduction of equipment size, or weight, this is not the only advantage that it offers and may in fact prove in many cases to be of secondary importance. In particular it has become increasingly apparent from recent system developments that a far more important factor in many applications will be reliability.

In modern computers and electronic switching systems there is a continual pressure towards greater overall circuit complexity resulting from a need to handle more data in a given time. The greatest barrier to advance in this direction is the reliability of the individual components and of their methods of interconnexion. The performance of present components, semiconductor devices, and interconnexions, is margin-

ally adequate at existing levels of complexity and considerable improvement is needed for the future. One of the main objectives of microminiature constructions is to achieve this improvement.

If we consider, for example, even a medium-sized computer, this may contain as many as 100 000 individual components, not including circuit interconnexions. As a result, even with an average individual component failure rate as low as 0·1% per 1000 hours, or one failure every million component hours of operation, the equipment would, on the average, only run for 10 hours between failures of one sort or another. At the worst these will stop the equipment operating and at the best will limit its capacity. With larger computers and the generally more complex data-handling systems envisaged for the future, the reliability required is correspondingly higher and individual component failure rates as low as 0·01%, and even 0·001%, per 1000 hours are being sought.

In the above example the effect of the intercomponent and intercircuit connexions was excluded. These items are, however, normally about twice as numerous as all other circuit components added together and since they can just as effectively contribute to system failures they need to be given at least equal consideration. In the past, largely no doubt as a result of their numbers, circuit interconnexions have in fact proved a major source of system faults. In many approaches to miniaturization a further aim has therefore been to eliminate as far as possible such connecting joints with a view to obtaining greater reliability.

Apart from the problem of increased reliability, more complex computer systems demand, in general, higher speeds of operation. The speed is ultimately limited by the time of transmission of electrical information through the system which in turn is determined by its physical dimensions. In order to operate at the highest digit rates it is therefore necessary to reduce the physical size of the circuits by some form of microminiaturization.

Other advantages that may be claimed for microminiature-type circuits are their greater ruggedness to withstand conditions of mechanical vibration and shock, their suitability to automatic production methods and, eventually, their lower cost. There is little evidence as yet to substantiate the last claim but, since they are unlikely ever to be produced except by largely automatic methods, it seems reasonable to assume that, once the basic technical problems have been solved, microminiature circuits will, in the long run, prove inexpensive.

METHODS OF APPROACH.

Most conventional electronic circuits consist essentially of interconnected arrangements of resistors, capacitors, and inductors, together with the necessary active elements, such as transistors, and non-linear elements, such as diodes.* The individual circuit elements are often considerably higher in voltage, current or power rating, and hence larger in size, than is demanded by their circuit functions. Little reduction in their size can, however, be made before difficulties are experienced in interconnecting them by conventional means, and new methods of approach are therefore necessary.

A more important factor in the reduction of size is the elimination of the large amount of waste space existing in present equipments. This occurs both within the components themselves, between components, and between mounting arrangements. The space occupied by those parts of the circuit which are essential to its operation rarely contributes more than 1 or 2% of the total volume. A main objective of microminiature circuits is therefore to eliminate this 'waste' space while at the same time tailoring the size of the components to the electrical requirements of the circuit.

A feature common to most approaches to microminiaturization in achieving this aim is the use of flat-type circuit elements of all kinds: resistors, capacitors, transistors, diodes, etc., and intercomponent connectors. These can be assembled together to give a good packing factor and hence little waste space. Inductors are much more difficult to achieve in this form and circuits requiring them are therefore, in general, not well suited to most methods of miniaturization. They may, however, in some cases be replaced by combinations of resistors, capacitors and active elements, or even by small mechanical resonant systems.

The various approaches to microminiature circuits can conveniently be divided into three categories:

(1) Unit component methods: in which single components are made individually and afterwards assembled and connected together to form a complete circuit module.

(2) Integrated circuits: in which a number of components are deposited together on a single insulating substrate to form a circuit unit.

(3) Solid circuits: where use is made of a semiconductor substrate within which are formed all the circuit elements both active and passive.

These divisions are, however, arbitrary and compromises between them exist, as will be seen later.

Much of the development work so far on all these methods has been done in America and most of the examples quoted will therefore come from this source. In this country much of the initial work has been done by the Royal Radar Establishment but recently this has been followed by a number of industrial organizations. In The General Electric Company, research and development work is proceeding at the Hirst Research Centre, Wembley, on the passive component and semiconductor aspects and consideration is also being given to the overall circuit and system problems.

UNIT COMPONENT METHOD.

This approach is best described in terms of the most well-known example of the method, the Micromodule concept, developed by the Radio Corporation of

* Thermionic valves have been omitted in what follows because, although some work on very small circuit units incorporating them has been done, they do not in general appear amenable to microminiature methods of construction.

America in conjunction with the United States Army Signal Corps.

Individual components are made up on thin wafers, about 0·3 in. square and 0·01 in. thick, provided with 12 connecting points round the circumference (fig. 1). The number of wafers needed to form a complete circuit are stacked on top of each other to give an approximately cubic unit and are then interconnected by vertical wires either hand- or machine-soldered to the appropriate connecting points on the edges of the wafers. The whole module is finally encapsulated in plastic with only those intercomponent leads projecting which are needed for subsequent interconnexion between modules.

The components themselves, which are essentially of flat form, can be made by a variety of techniques: evaporation, chemical deposition, printing, sputtering, etc., controlled by masking, mechanical abrading, etc. —as determined by the requirements of each component. The fact that they are separate items gives the system a considerable degree of flexibility since it allows each component type to be developed independently, and by different manufacturers if necessary, without conflict with the processing requirements of others. Some freedom in the choice of the thickness of any unit allows most types of components, including inductors, to be incorporated without significant influence on the overall component density achievable. This general flexibility makes the method suitable for a wide range of applications, including linear as well as digital circuit designs.

Further size compression is obtainable by the incorporation of more than one component per wafer as improvements in manufacturing techniques permit. This process can clearly be extended until major parts of circuits or even whole circuits are included on one wafer.

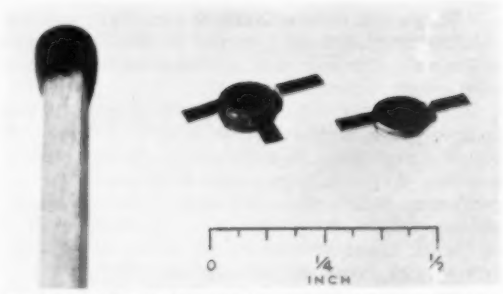

Fig. 2.—G.E.C. experimental microminiature diode and transistor designed for insertion into Integrated Circuit plates.

The basic, one component per plate, system is limited to a maximum component density of about 0·5 million per cubic foot. This is, however, sufficient to cover a very wide range of applications, including probably any that can be foreseen at present in the commercial field.

A potential disadvantage of the system is that it still includes soldered joints between all components and these have, in past designs of equipment, proved a source of unreliability. To what extent they will continue to do so will depend upon whether this unreliability has resulted from insufficiently controlled methods of soldering or from an inherent weakness of this method of connexion.

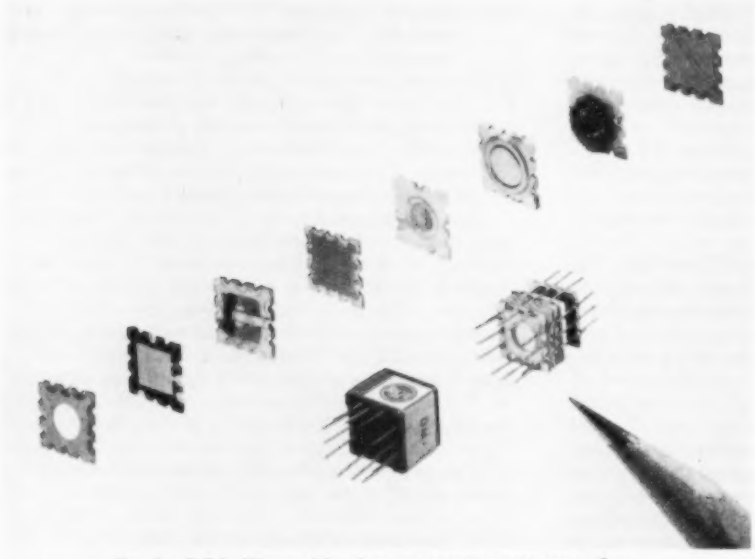

Fig. 1.—R.C.A. Micromodule, showing separate component wafers with method of assembly and connexion. (Courtesy of Radio Corporation of America.)

Integrated Circuits.

In this approach the circuit is very similar in general form to a reduced scale version of a conventional printed circuit except that flat-type components are used and most of these are formed, together with the intercomponent wiring, on the board itself. The components and wiring are normally built up on the basic insulating substrate by successive processes of either evaporation or printing, using conducting, resistive, and insulating layers, restricted to selected areas by masking. A very uniform surface is needed for the substrate to avoid uncontrolled variations in uniformity of the coating and to achieve this either glass or

special-grade ceramics are normally used.

Transistors and diodes, of a suitably small and flat form (fig. 2), have so far been produced as separate elements to be inserted into holes in the substrate subsequent to deposition of the passive components and wiring. Recent work in America, notably by Bell Telephone Laboratories and I.B.M., has however indicated that it may be possible eventually to produce transistors and semiconductor diodes also by vapour deposition processes. The size of a complete circuit of, say, 14 components would normally lie between 0·5 in. and 1 in. square with a thickness of about 0·05 in.

Experimental circuits of this kind have been developed in America by the Diamond Ordnance Fuze Laboratories, in their so-called 2D system, and in this country by R. R. E. Malvern under the name of Microcircuits. Fig. 3 shows a digital circuit in this form and fig. 4 an extension of the technique to linear circuits.

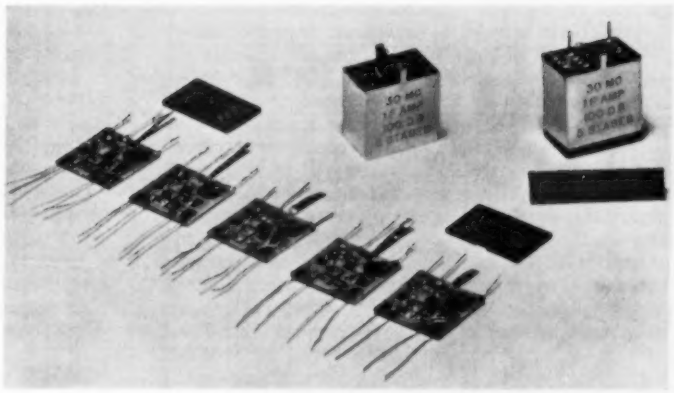

Fig. 4.—A 2D-Microelectronic version of a 100 dB, 30 Mc/s, 5 stage, i.f. amplifier, built by the U.S. Army Diamond Ordnance Fuze Laboratories. The complete amplifier, containing 5 transistors, 5 transformers, 20 capacitors and 25 resistors is mounted in a multicell screening can of less than 0·15 in³ overall volume. (Courtesy of Diamond Ordnance Fuze Laboratories.)

A main advantage claimed for this approach is the potentially greater reliability resulting from the absence of soldered joints between components. They are replaced by evaporated or printed connexions. The superior performance of these has yet to be established and the interconnexions between circuits, although smaller in number, have also still to be dealt with.

A major problem to be faced in this approach, and also in the more sophisticated methods to follow, is the achievement of a satisfactory yield of complete circuit units from a production process involving so many complex technical stages in series. The magnitude of this problem can best be illustrated by considering the relation between the yield for the individual component part processes and the resultant overall yield of complete circuit units. This is shown in fig. 5 from which it can be seen that, for a circuit plate containing say, 20 components, to be produced with a reject rate of not more than 30% would require an equivalent average reject rate for the individual component processes of less than 2%. Also, if the component reject rate increased to 4%, the overall reject rate would rise to 55%. This example probably gives an unnecessarily pessimistic picture since it assumes no correlation between the causes of individual component failure and also no means of checking component parts before the circuit is complete. Neither of these conditions is likely to hold fully in practice, nevertheless the example serves to illustrate the probable severity of the production problem.

The method is capable of a basic component-density of about 2-5 million per cubic foot and from this point of view is probably adequate for all applications except a small minority with very stringent space restrictions.

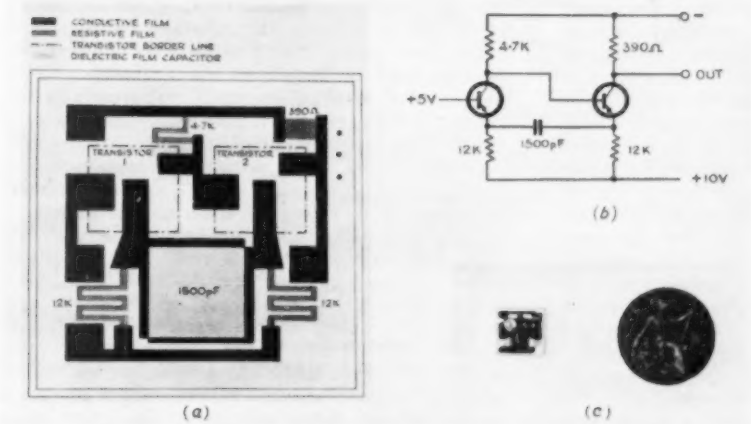

Fig. 3.—Experimental Microcircuit produced by R.R.E., using evaporation techniques together with separate insertion of transistors and diodes. (Crown copyright reserved, reproduced by permission of the Controller, H.M. Stationery Office.)

Solid Circuits.

If the substrate itself is made of semiconductor

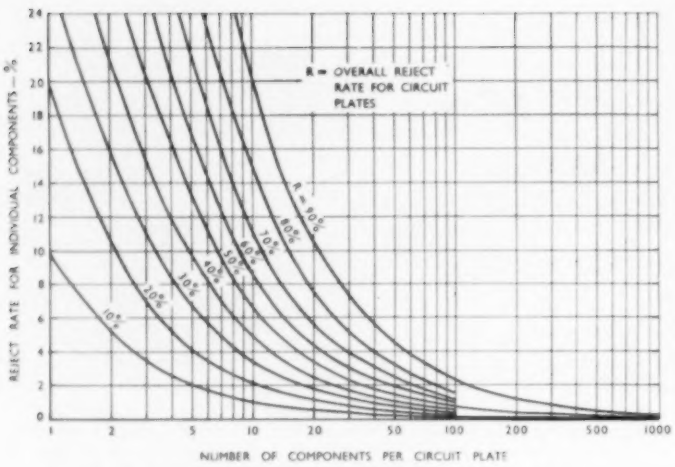
R = OVERALL REJECT RATE FOR CIRCUIT PLATES
REJECT RATE FOR INDIVIDUAL COMPONENTS — %
NUMBER OF COMPONENTS PER CIRCUIT PLATE

Fig. 5.—Integrated circuits: statistical variation of yield with number of components per circuit plate and with individual component reject rate.

material it is possible to form within it not only the necessary transistors and diodes but also resistors and capacitors by suitable localized treatment of different areas of the basic material using known techniques of diffusion, alloying, photo-masking, etching, machining, etc. 'Mesa' types of transistor and diode, for which manufacturing techniques are already well established, are directly applicable since their formation involves operating from one side of the semiconductor slice only. Resistors can be formed from the body of the material by varying its resistivity, through doping with suitable impurities, over restricted areas. Capacitors can also be obtained by utilizing the capacitance that exists across a reverse-biased p-n junction. The value is determined by the area and resistivity of the material used and so can also be controlled by a combination of diffusion and masking techniques. Interconnecting conductors between circuit components are largely dispensed

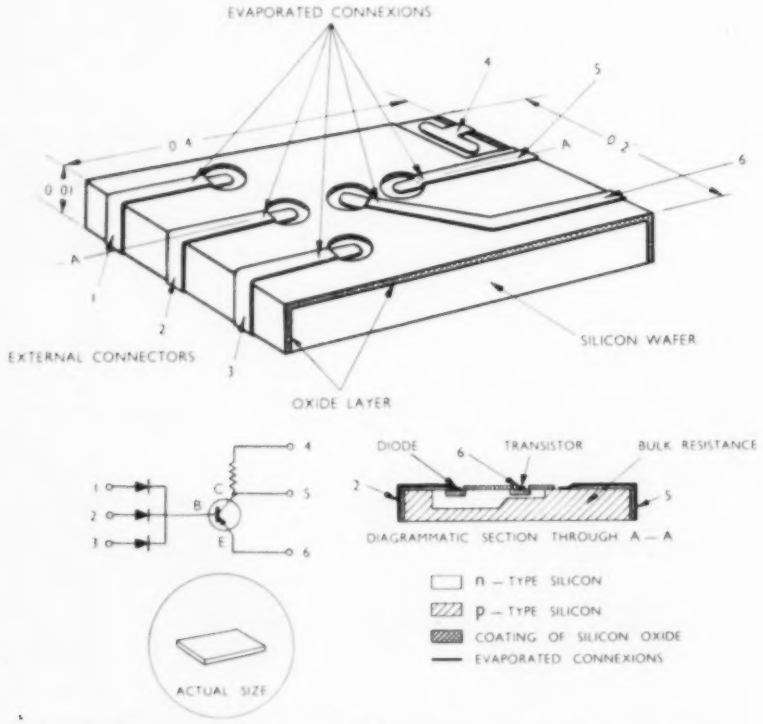

Fig. 6.—A proposed form of computer logic element using solid circuit techniques. The complete circuit, consisting of 3 diodes, 1 transistor, and 1 resistor is formed within a single wafer of silicon and interconnected by evaporated conductors.

with, since the components themselves form the bridges between the appropriate points on the circuit.

The method is clearly capable of giving very compact circuit units, and component densities as high as 30 million per cubic foot have been obtained. Since the circuit is, in effect, a solid block of material, very high reliability and great ruggedness can also be expected. Although the range of basic techniques necessary for making such circuits is known, and in fact developmental types have already been made, it would appear that formidable production problems still have to be solved before such units can be manufactured economically with satisfactory tolerances on components and with the range of performance needed in future switching systems. A possible form of computer logic circuit employing this technique is shown in fig. 6.

The solid circuit is limited at present in its flexibility both because of the restricted range of resistance and capacitance values readily available, and by the inherent interconnexions present between circuit elements which restrict the types of circuit that can be made. It is therefore likely that, for several years to come, at least, this method will be more readily employable in combination with the integrated circuit technique described above.

On the other hand it represents the most forward-looking approach to microminiaturization at present being developed and may well lead to quite novel circuit concepts in the future. In existing circuits of this type the individual components, as separate entities, have already largely disappeared and the next logical step in this direction is the formation of complete ' function blocks ', designed to meet specified input-to-output relations, without the need to refer back to traditional circuit structures in the design process. Functional units on these lines are already receiving serious consideration and experimental samples of various types have been made.

ADDITIONAL PROBLEMS.

Much of the work that has been done so far, and much that has been written, refers primarily to the problems and techniques of making very small circuit units by variants of one or other of the basic methods already described. There are, however, a number of other problems concerning the more general features of microminiature system design, that have to be solved before microminiaturization can be considered a practical reality.

The first of these is the problem of power dissipation and the means of cooling circuit-units and assemblies. Present power levels in low-power circuits are equivalent to some 10-20 milliwatts per component and, even with the minimum component densities visualized, normal thermal conductivities could give rise to internal temperatures well above 100° C for circuit assemblies of a few cubic inches in volume; for larger assemblies the situation becomes progressively worse due to the decreasing surface area to volume ratio. It is therefore clear that very efficient cooling systems will be necessary to keep internal temperatures down to acceptable limits. In addition, from the point of view of size reduction, the cooling system must be considered as part of the electronic equipment and must therefore itself be kept small.

The solution of this problem is unlikely to be provided by improved systems of cooling alone. Consideration needs to be given also to circuit designs which operate at much lower power levels, e.g. 1 mW per component or less, and to the design of transistors or other active devices which work efficiently at these low power levels. A device which may prove valuable in this connexion is the tunnel diode. Although still relatively new, and with much work still to be done to establish satisfactory circuit designs and device tolerances, it is capable of operating as a switch, or amplifier, both at frequencies of several hundred megacycles and at power levels below 1 mW.

The next general problem that has to be solved is that of interconnexion of circuit units and of circuit assemblies. Although many methods are available the provision of a solution, satisfactorily combining high reliability, compactness and ease of circuit maintenance, presents many difficulties. The problem of maintenance alone is likely to be severe since, for a long time to come, the economics of microminiature circuit manufacture are unlikely to permit, in most applications, the expenditure of more complex an item than a single circuit unit. In a complete system, units of this size must therefore be readily accessible for replacement.

Many of the circuit elements, and particularly the unprotected junctions of semiconductor devices, are sensitive to ambient atmosphere. Means of isolating them from its effects, without significant increase in the overall volume, will therefore be necessary if the high reliability aimed at is to be achieved. The means adopted will depend on, and may influence, the particular approach to microminiaturization. In those cases where individual components still appear, the sealing of them individually by modification of standard techniques may be desirable, while in other cases complete circuits, or even groups of circuits, may need to be sealed together as one unit. Recent developments in both plastic and low-melting-point glass coatings give some promise of a solution to this problem.

A further problem that as yet appears to have had little consideration is the interaction between adjacent circuits. With spacings of the order of 0·01 in. between components, intercircuit couplings are likely to be very high, both electrostatically, on account of the flat form of components and magnetically, in some cases, due to the low circuit impedances. The problem becomes increasingly acute with increase of speed and frequency and is likely to be serious in computers where decrease of size may be required primarily for higher speed.

When these general problems are taken into consideration it is clear that the component density figures normally quoted, which usually refer to those obtainable within a single circuit unit, will be extremely difficult to achieve in any major piece of equipment and may well have to be divided by a factor of at least 2 or 3 to give a practical operative figure. The greater the

intrinsic component density obtainable with any method the more difficult it will be to approach this value as an overall equipment figure due to the greater influence of these ancillary problems.

APPLICATIONS OF MICROMINIATURIZATION.

As has already been said the initial uses for microminiature circuits lie primarily in the military field, particularly in guided weapons and airborne equipment. Once satisfactory solutions for these needs have been established however there is little doubt that a much wider field of application will be found. Exactly how wide will depend, as much as anything else, on how successful the developments themselves are in achieving repeatable, reliable, low-cost elements. It is too early yet to make any accurate forecast but a brief review of some possible applications is perhaps worth while.

The majority of present computers are limited to digit rates of 1 Mc/s or less but there is continual pressure towards higher rates both to provide more rapid speed of operation in real-time problems and also to enable larger quantities of data to be dealt with more economically. As the rate is increased, however, the finite transmission time through the system, due to its physical size, becomes increasingly important. At digit rates somewhere between 10 Mc/s and 100 Mc/s these time-delays are likely to make present forms of circuitry unusable and they can only be reduced by a scaling down of the linear dimensions of the system, such as can be achieved by microminiature techniques.

Future satellite systems, whether for global communication, weather forecasting, or other purposes will require equipment of extremely small size and light weight and, although not all parts of such systems can necessarily be reduced to microminiature form, the maximum compression will be necessary wherever possible. While at present only in its infancy, this application appears to be one that will grow rapidly in importance over the next decade.

Apart from the requirements of military aircraft, there is always a pressing economic need for reduced weight in civil aircraft to give increased payload. Much, although not all, of the wide range of electronic equipment carried is amenable to microminiature construction. The reduction in weight, together with the expected increase in reliability, and hence lower maintenance, should help appreciably in reducing operating costs, particularly of the higher performance aircraft of the future.

The last field deserving mention is that of portable equipment where, in general, the equipment has to be carried during operation. The requirement is clearly for the smallest weight and size so as to reduce hindrance to normal movement to a minimum. Applications in this field are numerous and varied, ranging from mobile intercommunication equipment for military, police, and civil uses, to paging systems, hearing aids, and even miniature radio sets. Some of these, and more especially the last, will depend largely on economic factors for success.

In all these uses, apart from the guided-weapon and satellite applications where the very minimum of size and weight is necessary, a size reduction of about 10 : 1 over conventional constructions, or an equivalent component density of some 0·5 million per cubic foot, would appear to be adequate for a long time to come.

FUTURE INFLUENCES AND CONCLUSIONS.

It is as yet by no means certain which approach to microminiaturization is likely to prove most satisfactory in the future nor whether one approach alone can be sufficiently flexible to meet all needs. What is becoming increasingly clear is that in many applications the acceptability of any particular approach will depend more on the improvement in reliability it offers than on a maximum reduction in size. The assumption that greater reliability can in fact be achieved by the types of approach so far adopted is however still unproven and must remain so for some time to come.

If the more forward-looking developments, such as the solid-circuit approach, are eventually successful and become widely used, a revolution in thinking on the part of the equipment designer will be necessary. The smallest indivisible unit then available to him, in place of his present individual components, would represent some kind of circuit function, such as a bistable switch, a multiple gating circuit, or an amplifier. Also, for economic reasons, the variety of such circuit function units would necessarily be much more limited than those at present available from combination of individual components. Although these limitations may not appear serious to the designer of digital equipment, where much of his circuit detail already consists of multiple repetitions of a few relatively simple circuits, elsewhere quite new thinking will be needed. The influence of such developments may in fact be to bias designers in the direction of digital solutions to a far wider range of problems.

The use of microminiature systems on a large scale would also pose new problems to the manufacturing side of the electronic industry. Present boundaries between the realms of interest of the component manufacturer, the transistor manufacturer, and the equipment designer would largely disappear and new areas of individual interest would need to be accepted if the possibility of wholesale duplication of effort were to be avoided. This problem, although perhaps at present some way off, will need serious consideration before its solution becomes a matter of immediate urgency.

Highly Stressed 132-kV Oil-filled Cable installed at Melksham

By E. H. BALL, A.M.I.E.E., Pirelli-General Cable Works Ltd., Eastleigh.

ONE of the most important characteristics of a high-voltage cable is the maximum value of electric stress which occurs in the insulation at the operating voltage. In the normal case of a round conductor this stress is calculated from the well-known equation:

$$g = \frac{E_o}{r \log_e R/r}$$

in which E_o is the r.m.s. operating voltage (phase to neutral), and r and R are the radii of the inside and outside of the insulation respectively. The conductor is assumed to be a smooth cylinder, although this is not strictly true in the case of an unscreened stranded conductor.

Cables for 66 kV and above are normally designed today on the basis of a fixed value of operating stress for each system voltage, the insulation thickness necessary for any given conductor diameter then being calculated from the equation above. An increase in the value of stress chosen will result in a reduction of the insulation thickness for a given conductor size, and hence in a reduction in the overall diameter of the cable. Since the capital cost of a cable installation can be appreciably lowered by such a reduction, there is an economic incentive to increase the operating stress values to the highest possible levels. A limit is set in practice, however, by the obvious requirement that the cable should be capable of continuous service operation without breakdown, and also by the requirements of the specified Type Approval tests.

CHOICE OF OPERATING STRESS.

In the case of oil-filled cables the present limitation of operating stress is usually set by the requirements of the Impulse Withstand Test which forms part of the Type Test Specification. The requirements of this test are designed to ensure that the cable system has adequate impulse strength to withstand the voltage surges to which it may be subjected in practice. Table 1 lists the Impulse Withstand voltages, corresponding with each system voltage, specified by the Central Electricity Generating Board (C.E.G.B.).

TABLE 1.
OPERATING AND TEST STRESSES FOR HIGH-VOLTAGE CABLES.

System voltage kV	Specified impulse withstand voltage kV	Maximum operating stress of present P.G. cable designs kV/cm	Stress in the dielectric at impulse withstand voltage kV/cm
33	193	83	840
66	342	100	900
132	640	125	1050
275	1050	150	990
400	1425	160	990

The table also lists the present-day values of cable operating stress for which Pirelli-General have obtained C.E.G.B. Type Approval, together with the corresponding values of maximum stress in the insulation at the specified impulse test voltages. It will be seen from this table that, although an operating stress of 160 kV/cm is perfectly feasible in the case of a 400 kV cable, the 132 kV cable, with an operating

stress of only 125 kV/cm, is actually a more highly stressed design when considered in relation to the impulse test.

The values of operating stress quoted in Table 1 reflect the considerable advances that have been made in oil-filled cables during the thirty-two years since the first installation was made in Great Britain. The cable industry is sometimes criticized on the ground that the insulating material in use for high-voltage cables, namely oil-impregnated paper, has remained basically unchanged for many years, but it is wrong to assume that no progress has been made. The value of operating stress in use at any time may be taken as an index of the quality of the dielectric of that particular period, and fig. 1 illustrates the progress in quality that has been made. Until 1948, cables were designed on the basis of a fixed insulation thickness rather than a fixed maximum stress. In fig. 1, therefore, a typical conductor size of 0·4 in² has been chosen, and the stresses quoted in all cases relate to the insulation thickness in question applied to the assumed conductor diameter. Fig. 1 also shows the corresponding physical dimensions, illustrating the reduction which has been achieved.

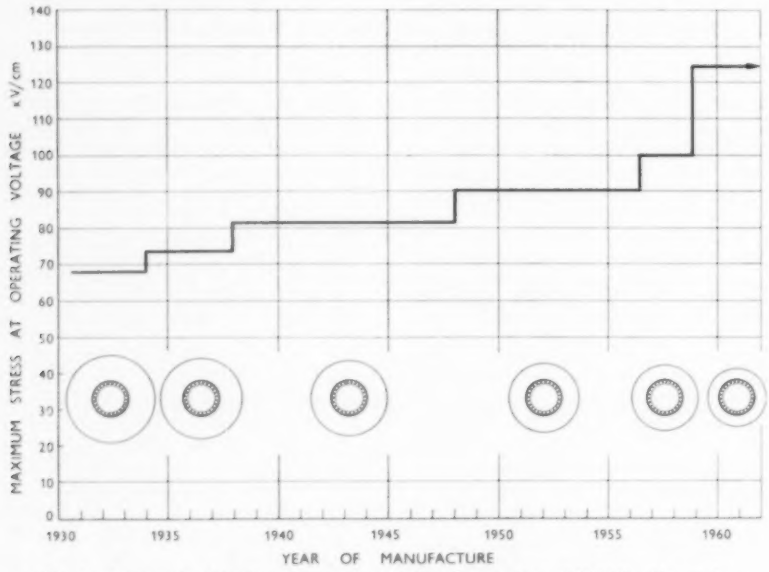

Fig. 1.—Increase in operating stress and reduction of dimensions of 132 kV cables made by Pirelli-General Cable Works over the past thirty years.

The improvements which have enabled such considerable increase in stress to be made are described in detail in a recent paper.[1] The main items are:

improvements in conductor screening, the introduction of special papers of high strength, and improvements in manufacturing technique resulting from a scientific study of the paper-lapping process.

3-CORE 132 kV 125 kV/cm CABLE.

As already mentioned, cables for 132 kV with an operating stress of 125 kV/cm may be regarded as perhaps the farthest advance yet in the trend towards higher stresses—a trend which has been fostered by the increasing emphasis placed by the C.E.G.B. on economy of capital cost, and also by the highly competitive conditions which have existed in the cable industry in recent years.

It is not surprising therefore that this cable design has aroused considerable interest and some controversy. In spite of the exhaustive laboratory testing to which the design has been subjected, it has been suggested that the operating stress has been advanced to a level such that the normal safety margins have been cut and the cable may not be able to withstand satisfactorily the hazards of laying and jointing.

These questions have been the subject of discussions between the C.E.G.B. and representatives of Pirelli-General which, at a meeting in May 1959, finally led to an agreement that before acceptance of the design for general use a trial installation should be made and operated for a period of three years. The C.E.G.B. further asked that dielectric power-factor tests should be made immediately after installation and after the three-year trial period, and that the circuit should then be removed from service and a section of the length returned to the Works for a repeat of part of the Type Tests. This trial installation is now in service, and before describing it further it is of interest to review briefly the laboratory tests carried out on the cable design.

LABORATORY TESTS.

New designs of oil-filled cables and accessories intended for use by the C.E.G.B. are type tested to the requirements laid down in the C.E.G.B. Engineering Recommendation C/28. This document specifies a number of tests, of which the most important from the point of view of the insulation design are the Loading-Cycle and Thermal-Stability Tests and the Impulse Withstand Test. Each of these tests is done on an assembly which constitutes a miniature cable system, including each kind of accessory that may be used in an actual installation.

For the loading-cycle test the assembly is heated by passing current through the conductors until the conductor reaches 5° to 10° C above the normal maximum operating temperature, this temperature being maintained for three hours and the assembly then allowed to cool. This cycle is repeated daily for twenty days, and during the whole period a voltage of $1\frac{1}{2}$ times the working value (in the case of 132 kV cable) is maintained on the conductor, power-factor measurements being made before and during each loading cycle. The object of this test is to show that no progressive increase of power factor occurs as a result of thermal cycles.

The thermal-stability test immediately follows the loading-cycle test. It consists of a further heating cycle under the same conditions, but with current and voltage maintained constant, until for a continuous six-hour period the variations of conductor and sheath temperature do not exceed a total change of 2° C (allowing for ambient changes).

The object of this test is to show that there is no tendency towards thermal instability in the dielectric, which would arise if the rate of heat generation within it exceeded the rate of dissipation. Since the test is done at $1\frac{1}{2}$ times working voltage, and dielectric power loss is proportional to the square of the voltage, the test conditions represent a considerable margin of safety over practical conditions.

The impulse withstand test consists of the application to the test assembly of 10 successive negative followed by 10 successive positive impulses, of nominal 1 : 50 μs wave shape and of peak value as given in Table 1. During this test the assembly is heated to a conductor temperature 5° C above the maximum operating temperature.

No high-voltage a.c. test is specified by the C.E.G.B., but the International Electrotechnical Commission specifies a test consisting of the application of an alternating voltage of $2\frac{1}{2}$ times the normal operating voltage for 24 hours. It has always been the view of Pirelli-General engineers that this test is necessary to prove the soundness of the design of a cable and its accessories, and it is normal practice to carry out the test on all new P-G designs.

The tests on the 132 kV 125 kV/cm cable were done on an assembly consisting of 40 yards of 3-core 0·6 in² cable and including the following accessories:

3-core straight joint.
3-core stop joint.
Trifurcating joint.
Splitter box.
Outdoor sealing ends.
Oil-immersed sealing end.

After preliminary testing, the full range of type approval tests described above was carried out first for the normal maximum conductor temperature of 85° C, the impulse withstand test being extended to include 10 negative and 10 positive impulses at 660 kV in addition to those at the specified withstand voltage of 640 kV. The 24-hour test at $2\frac{1}{2}$-times operating voltage was also included both before and after the impulse test.

This whole series of tests was then repeated, but for the higher maximum conductor temperature of 115° C. Each of the hot tests was thus carried out at a temperature 30° C higher than for the first series of tests, and the successful results demonstrate the very considerable overload capacity of the cable system. Other investigations[2] have shown that the rate of degradation of the mechanical characteristics of the insulating paper increases rapidly with temperature and that prolonged operation at temperatures of this order would appreciably reduce the life of the insulation. During emergency overload conditions, however, for limited periods, operation at temperatures up to 115° C or even higher is quite feasible.

Following the success of the above tests, the same assembly was subjected to further tests in which the conductor was maintained at a high temperature continuously, with twice the normal operating voltage applied. The conductor temperatures of the three cores were 120° C, 123° C, and 134° C. The core at the highest temperature broke down after 33 days, owing to thermal instability arising from a mistake in adjustment of the loading current. The other two cores continued to operate satisfactorily for a further 78 days under these conditions, and were then finally subjected again to the 24-hour test and an impulse breakdown test, both cores breaking down at 680 kV adjacent to the spot in the cable where the first core had failed.

In addition to the very extensive electrical tests outlined above, this cable design has also been subjected to an unusually severe bending test, intended to demonstrate the ability of the cable to withstand the bending and handling required during laying operations in the field.

The minimum bending radius used during installation is twelve times the overall diameter of the cable, and the bending test called for in the C.E.G.B. Type Test specification is ten times the (smaller) sheath diameter. The special bending test was carried out at a radius of six times the sheath diameter and thus represents bending rather more than twice the most severe permitted in practice. The bending test consisted of three cycles, as in the Type Approval Test specification, each cycle comprising two bends in opposite directions. The cable length was then carefully examined, and the lapped paper insulation was found to be completely free of tears or creases with the registration of the tapes of the same consistency as in a new cable.

TRIAL INSTALLATION AT MELKSHAM.

The erection of a 275 kV transmission line to Melksham substation, near Bath, in 1960 necessitated the taking underground of two existing 132 kV lines at the point where they were crossed by the new 275 kV line near Melksham. This was the site chosen by the C.E.G.B. for the trial installation of 132 kV 3-core 125 kV/cm cable, and a length of 565 yards of 0·40 in² cable of this design forms one of the underground cable links. Although not necessary for the installation in question, a stop joint and a trifurcating joint were included in the circuit, which was terminated at both ends with outdoor sealing ends.

every oil-filled cable manufactured, but the requirement that this test should be done at working voltage after laying is very unusual and required special arrangements to be made. The normal method of measurement is by means of the high-voltage Schering-Bridge circuit, which requires the cable sheath to be at a small voltage above earth and to have a low capacitance to earth, and since the cable under test is normally wound on a wooden drum this presents no difficulty.

When the cable is laid and buried, however, although the anticorrosion protection over the sheath is quite adequate to withstand the small voltage necessary between sheath and ground, the very large capacitance

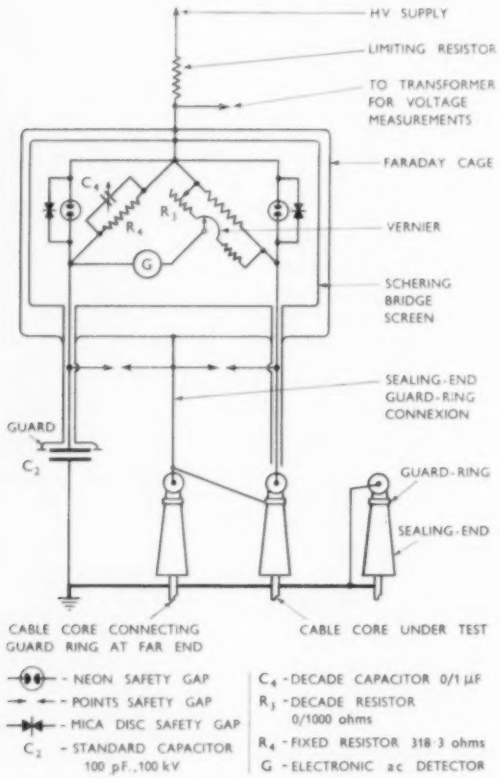

Fig. 2.—Circuit diagram for power-factor measurements.

The installation and jointing of the cable followed the normal practice and no difficulties or delays occurred. The cable was laid and jointed during March 1960 and was made alive in April, following the normal d.c. test of 264 kV for 15 minutes. Although the C.E.G.B. had stipulated that a power-factor test should be done immediately after installation, it was not possible to release the feeder for this purpose until August 1960.

Power-factor tests are carried out in the Works on

between the sheath and ground would introduce an error if the normal Schering-Bridge circuit were used. This error could be calculated and allowed for, but to avoid any uncertainty in the final result it was decided to adopt the ' inverted Schering-Bridge ' circuit, which enables the sheath to be directly earthed and hence eliminates the source of error. The inverted Schering-Bridge requires the operator and all normally low-voltage parts of the bridge circuit to be at high potential, in this case 76 kV above earth, and to make

this possible with safety a ' Faraday Cage ' was used to house the operator and bridge controls.

The Faraday Cage consisted of a wire-mesh cage 6 ft × 3 ft × 6 ft 6 in. high, with rounded corners, mounted on insulators about 5 ft from the ground. The normally low-voltage arms of the Schering-Bridge were housed in the cage, and the detector was operated from a battery-fed rotary converter also within the cage.

The supply for carrying out the test was taken from a 30 MVA transformer in Norrington substation, and a resistor of 2800 ohms was interposed between the supply and the bridge circuit, to limit the current in the event of a flashover or breakdown of the measuring equipment or cage supports. Fig. 2 shows the circuit diagram of the test arrangement. Each of the three cable cores was tested separately, with guard rings fitted to the porcelain surfaces of the sealing ends to eliminate the effects of surface leakage.

Fig. 3 shows the cage in use with a Pirelli-General engineer operating the bridge and Mr. C. C. Barnes of the C.E.G.B. witnessing the measurements.

As expected, the measured power-factor was found to be almost identical to that obtained on the length of cable during the routine tests in the Works, indicating that no deterioration had occurred during installation and jointing, or during the few months the cable had been in service.

The power-factor test will be repeated in April 1963, at the end of the three-year trial period and, as agreed, a section of the cable length will then be returned to the Works for further tests. It is confidently expected that no deterioration will have occurred and that the trust of Pirelli-General engineers in the soundness of their design will be fully justified.

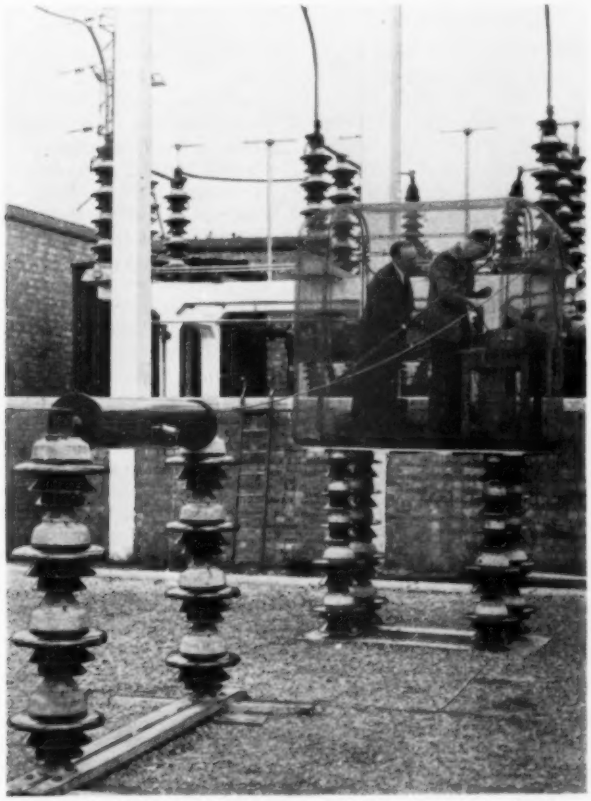

Fig. 3.—Power-factor measurements being carried out inside the Faraday cage.

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High-frequency Germanium Transistors

By B. A. I. DAVIS, B.Sc., Hirst Research Centre

IN recent years considerable progress has been made in the development of germanium transistors for high-frequency operation. The maximum cut-off frequency has been successively increased with the development of the drift and mesa structures, which have overcome the major limitations of the alloy transistor and enable the close dimensional tolerances necessary for the manufacture of high-frequency transistors to be controlled with sufficient accuracy.

ALLOY TRANSISTOR.

The cut-off frequency of the alloy transistor results from dispersion of the carriers (holes for *p-n-p*, electrons for *n-p-n*) crossing the base region by a diffusion process, and is inversely proportional to the square of the base width. Fig. 1 shows the cut-off frequency of the alloy transistor as a function of base width and it can be seen that high cut-off frequencies call for very narrow base regions which become increasingly more difficult to control using alloy techniques. The major limitation of the alloy structure, however, arises from the onset of 'punch through' at a low voltage as the base width is decreased. This results from the extension of the collector depletion (space charge) layer across the base region with increasing applied voltage until, at the punch-through voltage, it reaches the emitter junction and effectively short-circuits the transistor. Since the depletion layer width is proportional to the square root of the resistivity of the semiconductor material in the base region, the punch-through voltage can be increased if the base resistivity is reduced. This is only possible to a limited extent with the alloy structure, without causing an excessive reduction in the collector breakdown voltage and increase in the collector capacitance. Bearing in mind the tolerances that must be accepted in the various manufacturing processes, the factors mentioned above limit the maximum designable cut-off frequency of the *p-n-p* alloy transistor to about 15 Mc/s. The *n-p-n* structure offers some theoretical advantage due to the higher mobility of the carriers (electrons), but this is largely offset by the greater manufacturing difficulties and also by the fact that the capacitance (per unit area) of its *p-n* junctions is greater.

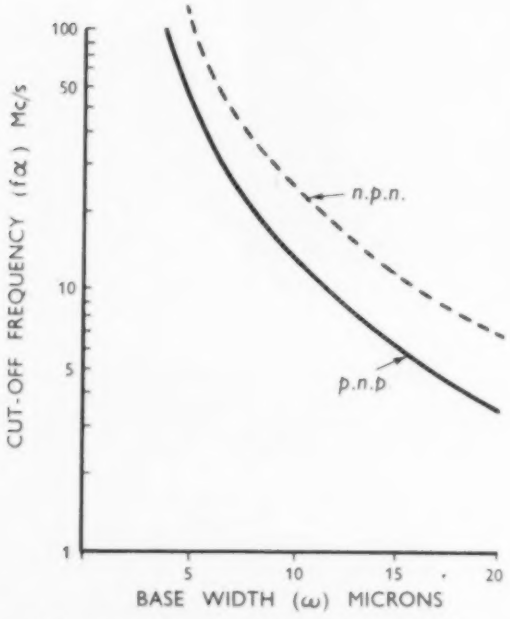

Fig. 1.—Cut-off frequency of alloy transistor v base width.

DRIFT TRANSISTOR.

The apparently contradictory requirements, for high-frequency operation, of low base resistivity, high collector-breakdown-voltage and low collector capacitance, incompatible with the alloy structure, can be satisfied with the graded base structure shown in fig. 2. This illustrates the construction of the drift transistor first described by Kroemer in 1953.[1, 2, 3] The essential feature of this design is the variation in the impurity concentration across the base region, it being high at the emitter and low at the collector junction. The graded base region is formed by the diffusion of an *n*-type impurity such as antimony or arsenic into a high-resistivity (20-30 Ω cm) *n*-type germanium wafer to form a low resistivity *n*+ skin at the surface, fig. 2(*a*). The diffusion is carried out with a vapour source in a hydrogen or vacuum furnace, and provided the time to reach surface equilibrium is short compared to the diffusion time the impurity concentration in the diffused layer will follow a complementary error-function distribution. The surface concentration is determined by the vapour pressure of the diffusant, and the depth of the diffused layer by the time and

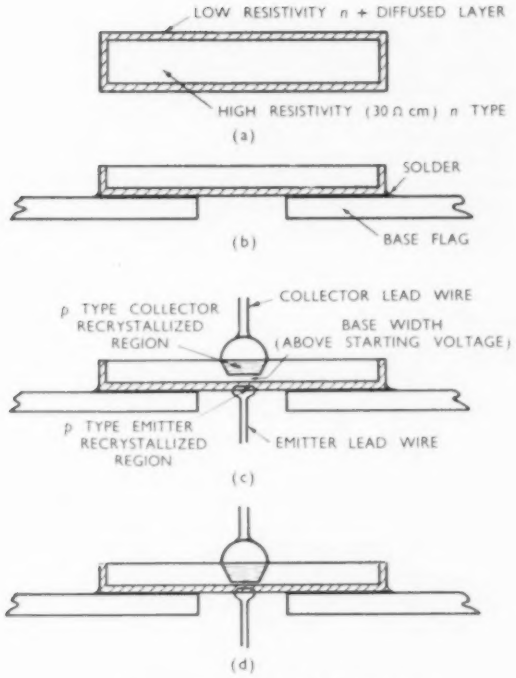

Fig. 2.—Manufacture of drift transistor.

(a) Diffused wafer.
(b) Diffused wafer etched and mounted on base flag.
(c) Completed drift transistor.
(d) Switching version of drift transistor.

temperature of the diffusion. As the process is relatively slow great accuracy can be obtained.

A typical diffusion profile suitable for the manufacture of a 100 Mc/s drift transistor is shown in fig. 3. The surface concentration is 5×10^{17} atoms/cc and the depth of the diffused layer 10μ. This corresponds to diffusion for 1 hour at 780° C from an antimony source.

After diffusion the diffused layer is removed from one face of the wafer by chemical etching after first masking the other face with wax. A base contact is soldered to the diffused face, fig. 2 (*b*), and the emitter and collector junctions are formed in the low- and high-resistivity regions respectiviely by alloying, fig. 2(*c*). The collector junction, beng formed in a region of. high resistivity, has a very low capacitance and high breakdown-voltage.

The exact position of the collector junction is not critical. The collector depletion layer extends rapidly across the high resistivity portion of the base region with applied voltage until, at a low voltage (the starting voltage) it reaches the heavily doped $n+$ layer. Above this voltage the width of the depletion layer is virtually constant, for any further movement would take it into a region of rapidly increasing impurity concentration. The diffused base region thus prevents punch-through to the emitter and furthermore it effectively defines the base width at voltages in excess of the starting voltage. The base width depends on a single shallow alloying operating at the emitter and on the depth of the diffusion. It is more easily controlled in this way than in the alloy construction, where it is determined by two relatively deep alloying processes.

A further advantage accrues from the establishment of a drift field in the base region, as a result of the graded impurity concentration. This field is in the direction to accelerate the carriers and thus to reduce the carrier transit-time, raising the cut-off frequency to some three to four times that of the alloy transistor. The cut-off frequency is however limited by the capacitance of the p-n junction at the emitter, together with the a.c. resistance of the emitter junction. The emitter transition capacitance, *Ce*, is relatively large because of the high impurity concentration at the emitter junction, and can be reduced only by reducing the emitter junction area. The size of the emitter junction is therefore of major importance in the design of a drift transistor and should be kept as small as possible. A 100 Mc/s drift transistor has a typical emitter diameter of 0·006 in. and is formed by alloying a 0·005 in. diameter indium gallium sphere. Although it is possible to use smaller emitter dots the problems of handling them and making electrical contact become increasingly more difficult.

The cut-off frequency of the drift transistor depends markedly on the emitter current. As the current is increased the limiting effect of *Ce* is reduced due to the reduction in r_e, the a.c. resistance of the emitter junction, which is inversely proportional to the current.

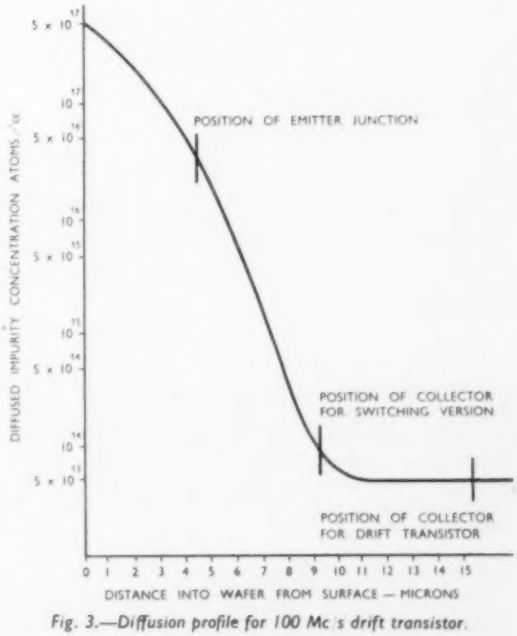
DIFFUSED IMPURITY CONCENTRATION ATOMS / cc
POSITION OF EMITTER JUNCTION
POSITION OF COLLECTOR FOR SWITCHING VERSION
POSITION OF COLLECTOR FOR DRIFT TRANSISTOR
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
DISTANCE INTO WAFER FROM SURFACE — MICRONS

Fig. 3.—Diffusion profile for 100 Mc/s drift transistor.

This causes an initial rise in the cut-off frequency, f_1, as shown in fig. 4. At high current levels the magnitude of the drift field is reduced, as a result of the charge distribution set up in the base. This leads to the subsequent fall in f_1 at high current.

The variation of cut-off frequency with collector voltage is shown in fig. 5. Above the starting voltage f_1 remains virtually constant, but below the starting voltage f_1 falls rapidly as the collector depletion layer falls back into the high-resistivity region, so increasing the base width.

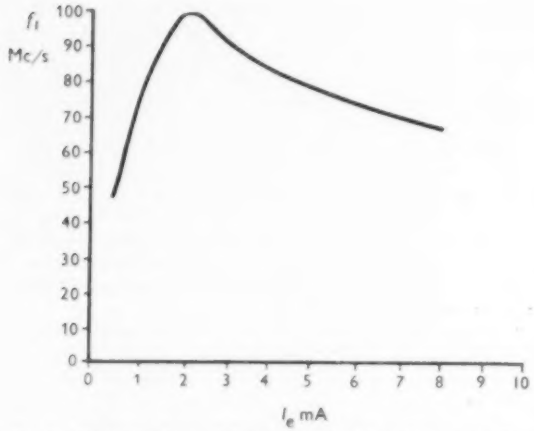

Fig. 4.—Variation of cut-off frequency (f_1) with emitter current for a drift transistor.

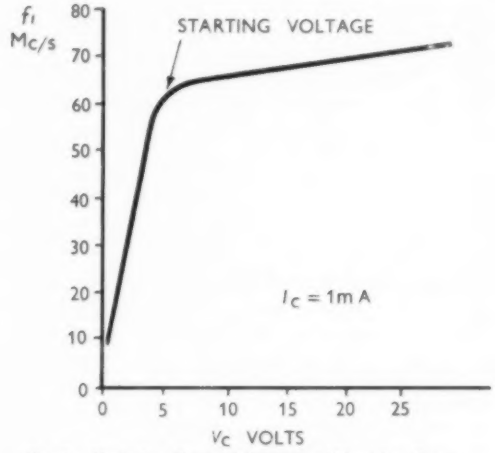

Fig. 5.—Variation of cut-off frequency (f_1) with collector voltage for a drift transistor.

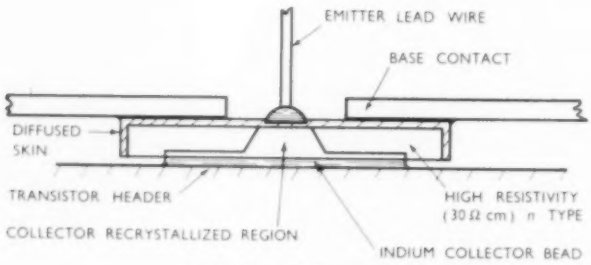

Fig. 6.—Power drift transistor.

Although in mixer and amplifier applications a small starting voltage is not a serious embarrassment, in most switching applications it is important that the cut-off frequency is maintained at low values of collector voltage. It is then necessary to modify the structure by alloying the collector junction right up to the diffused region, fig. 2 (*d*).

High-Power Operation.

The drift structure can be modified for high-power operation by alloying a second larger-area collector junction, superimposed on the first, into the high-resistivity region (fig. 6) and then mounting this collector on the header, following standard power-transistor practice.[4] The features of this construction are low electrode capacitance, and good saturation characteristics. A cut-off frequency of 100 Mc/s is feasible with an allowable dissipation of several watts at room temperature. Transistors of this type are particularly suitable for fast high-current switching, and power amplification at frequencies of up to 30 Mc/s.

Mesa Transistor.

The manufacture of drift transistors with cut-off frequencies much in excess of 100 Mc/s is rendered difficult by the problems of controlling the emitter alloy penetration and the emitter capacitance. These problems can be overcome if evaporation techniques are used to form the emitter electrode. These techniques, which lend themselves to a high degree of control are particularly suited to the mesa form of construction[5] shown in fig. 7. The transistor is again constructed in a region of graded impurity concentra-

tion, but in this case the collector junction is formed by diffusion and the emitter and base electrodes by evaporation. Very close emitter-base spacings are possible and this, together with the rectangular symmetry used, helps to reduce the base resistance.

Starting with a *p*-type wafer, an *n*-type impurity is diffused in to form a *p*-*n* junction at a point below the surface where the concentration of the diffused *n*-type impurity is equal to the background *p*-type concentration, fig. 7(*a*). The diffused layer is removed from one face of the wafer and stripes of aluminium and gold antimony are evaporated side-by-side on to the diffused surface through a mask, fig. 7(*b*). The stripes are alloyed to the germanium by raising the wafer temperature, the aluminium stripe forming a *p*-type emitter region and the gold antimony stripe an ohmic base contact. After masking the area of the stripes with wax, the remainder of the diffused layer is removed by chemical etching to form the mesa and reduce the collector junction area and hence the collector capacitance. The masking wax is finally removed, the transistor soldered to the header and contacts made to the emitter and base stripes with thin gold wire by thermo-compression bonding, [6, 7, 8, fig. 7 (d).

With this form of construction cut-off frequencies in the kilo megacycle range are possible, but this calls for very small stripe and mesa areas to minimize the limiting effect of the electrode capacitances, very close stripe-spacing to give low base resistance, and very thin diffused layers. For a transistor designed to operate at 1000 Mc/s the thickness of the diffused region would be only 0·3μ and typical stripe dimensions and spacing 30$\mu \times 15\mu$ and 10μ respectively. The whole transistor is formed in a region within a fraction of a micron of the surface, and considerable attention has to be paid to the initial preparation of the surface of the germanium wafer.

A great advantage of the mesa construction lies in the ability to make a large number of transistors at one time, using an evaporation mask with multiple slots. Fig. 8 shows a wafer of germanium on which 25 pairs

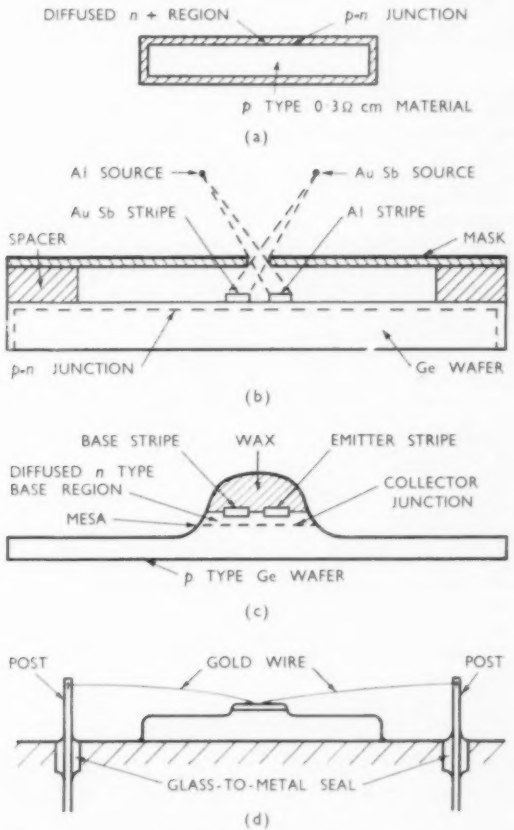

Fig. 7.—Mesa transistor.

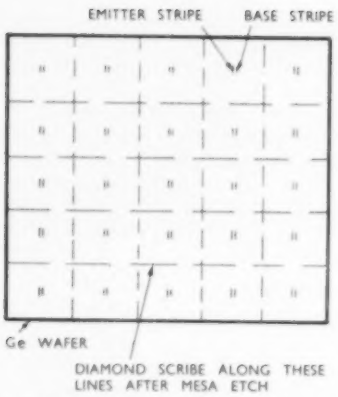

Fig. 8.—Germanium wafer with 25 pairs of evaporated stripes.

of stripes have been evaporated using a mask with 25 slots. This wafer can be processed as a single unit as far as mesa etching, after which it is diamond-scribed and broken up to give 25 transistors. Only the final mounting and thermo-compression bonding operations have to be done as individual processes. Because of the very tiny dimensions involved it is possible to make as many as 1000 transistors at a time in this way and to reduce manufacturing costs. For this reason it has been claimed that eventually the mesa transistor will be cheaper than the alloy transistor.

High-Power Operation.

A disadvantage of the mesa transistor for high-power operation is the relatively large collector series-resistance associated with the *p*-type collector body. This can be reduced by modifying the structure as shown in fig. 9 using newly developed epitaxial techniques [9, 10], which enable a high resistivity *p*-type region to be grown on a low-resistivity *p*-type substrate. A low-resistivity $n+$ skin is diffused into the high-resistivity region and a mesa transistor constructed. The thin high-resistivity region ensures high collector-breakdown voltage and the low-resistivity substrate a low collector series resistance. For very-high-current operation it may also be necessary to use comb-like emitter and base electrodes to reduce the current density.

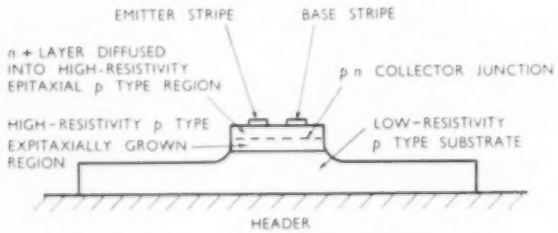
EMITTER STRIPE
BASE STRIPE
n + LAYER DIFFUSED INTO HIGH-RESISTIVITY EPITAXIAL p TYPE REGION
p n COLLECTOR JUNCTION
HIGH-RESISTIVITY p TYPE EXPITAXIALLY GROWN REGION
LOW-RESISTIVITY p TYPE SUBSTRATE
HEADER

Fig. 9.—High-power, high-frequency epitaxial transistor.

Future Developments.

Considerable progress has already been made in the design of high-frequency germanium transistors, and cut-off frequencies of over 1000 Mc/s are now feasible. Further advances may result in the future from the use of new intermetallic semiconductors with higher carrier mobilities and higher energy gaps. With indium antimonide, cut-off frequencies of tens of kilo megacycles may be possible, while the large energy gap (1·4 *eV*) of gallium arsenide should allow higher power dissipation, or higher operating temperatures, with cut-off frequencies comparable with germanium.

Apart from advanced research on u.h.f. structures which should lead to a more complete understanding of the processes involved, and the ultimate limits of cut-off frequency possible, current development programmes being undertaken by the Company include work on epitaxial techniques and lower frequency (f_t 500 Mc/s) mesa transistors such as the EW91. These will be needed in large numbers in a few years time for television and high-speed data-processing applications, if the promise of low manufacturing cost can be realized.

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Progress in Research on High-pressure Mercury Vapour Lamps

By E. H. NELSON, Hirst Research Centre.

A review of recent progress in research on high-pressure mercury vapour lamps of the type used for general lighting services. Improved techniques for manufacture and new forms of self-ballasted lamps are described. The limits of luminous efficiency improvement and the use of added metal vapours to improve luminous efficency or colour properties are discussed.

This article is based on a paper read to the Association Francaise de l'Éclairage at Rouen in May, 1961, to be published in the November issue of 'Revue Lux'.

INTRODUCTION.

THIS article describes recent work on high-pressure mercury vapour lamps of the type used for general lighting purposes. It is not concerned with high-brightness, concentrated-arc lamps; nor does it consider in any detail the work on phosphors for hpmv lamps reviewed by Jenkins and McKeag.[1]

General lighting service hpmv lamps have the following characteristics:

(*a*) Operation from ordinary mains voltage supplies.
(*b*) A life of several thousand hours at high luminous efficiency.
(*c*) A discharge tube which is long compared with its diameter.
(*d*) An arc wattage loading in the range 20-80 watts/cm.
(*e*) A mercury vapour density in the range corresponding to 8-30 volts/cm.
(*f*) A protective outer envelope which may or may not be phosphor-coated on the inside wall.

Lamps of this type were first used for public lighting in 1932 and have reached a position of such importance in public lighting that much effort is being devoted in many countries to their improvement and development.

All the work reported here is experimental and much of it is still far from complete. The intention is to provide an account of improvement and development and an indication of what may be achieved in the near and distant future.

For convenience the work has been divided into four parts:

(*a*) Improvements in existing lamp types.
(*b*) Extension of existing lamp range.
(*c*) Luminous efficiency of the discharge.
(*d*) New types of lamp.

IMPROVEMENTS IN EXISTING LAMP TYPES.

Electrode Design.

The lumen maintenance of hpmv discharge tubes in fused-silica envelopes is almost entirely determined by the behaviour of the electrodes. Problems of silica deterioration during lamp life are now solved and, ignoring possible deterioration of phosphors, the only remaining cause of loss of light during lamp life is obscuration of the silica lamp body by material evaporated or sputtered from the electrodes. It is, therefore, of great importance to understand the controlling features of electrode design.

A pecularity of hpmv lamp electrodes is that they must operate in two entirely different discharge régimes, according to whether the lamp is in the low-pressure starting condition or the high-pressure running condition. Fortunately the required life in the low-pressure condition is short—of the order of 30 hours—nevertheless it is necessary to design for both low- and high-pressure operation and, in fact, hpmv electrodes are usually made in two distinct parts incorporated in one body.

Fig. 1 shows an electrode design which lends itself to experimental study. The main electrode body is a relatively massive rod of tungsten cut away to receive a compound which will react slowly with tungsten to form very small quantities of free barium metal which condense on the surface of the tungsten and improve its electron-emitting properties. Surrounding the rod and emitter is a relatively light coil of tungsten wire.

An electrode of this type may be easily modified to give excellent performance in any size of lamp. The tungsten coil dimensions may be adjusted to provide a low-pressure electrode, while the diameter of the tungsten rod and the distance between the tip of the rod and the emitter may be adjusted to control the rate

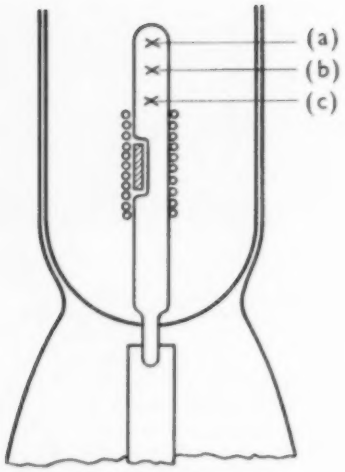


Fig. 1.—Electrode for hpmv lamp.

of heat conduction from the arc point at the rod tip and the temperature at which the emitter operates.

It has been found with electrodes of this type that excellent performance in the high-pressure state may be obtained with barium activation if the tip of the rod where the arc terminates is maintained at an apparent temperature between 1400° C and 1500° C. This temperature is not easily measured directly but, for design purposes, it is satisfactory to measure the rod temperature with an optical pyrometer at several points (*a*, *b*, *c*, fig. 1) and then extrapolate the measurements to give a figure for the electrode tip.

The mechanism of operation of electrodes in the high-pressure arc is still imperfectly understood. Attempts to estimate the voltage drop at the electrodes indicate that, in the lamps under consideration, the total voltage drop for well-designed barium-activated electrodes is remarkably independent of operating conditions at about 17 volts, of which about 8 are lost at the cathode and 9 at the anode.

The precise chemical composition of the emitter material is not critical. The important point is to adjust the temperature of operation of the emitter so that barium is evolved at a rate just sufficient to supply the necessary activation. In general the composition of the emitter material will be decided from practical considerations such as ease of manufacture and chemical stability on exposure to the atmosphere.

Gas Content of Fused Silica.

Maximum luminous efficiencies are obtained by operating at high mercury vapour pressures and high wattage loadings per unit length of arc. This implies high operating temperatures for the discharge tubes and the use of fused silica rather than glass for the discharge tube bodies. Fused silica has the further

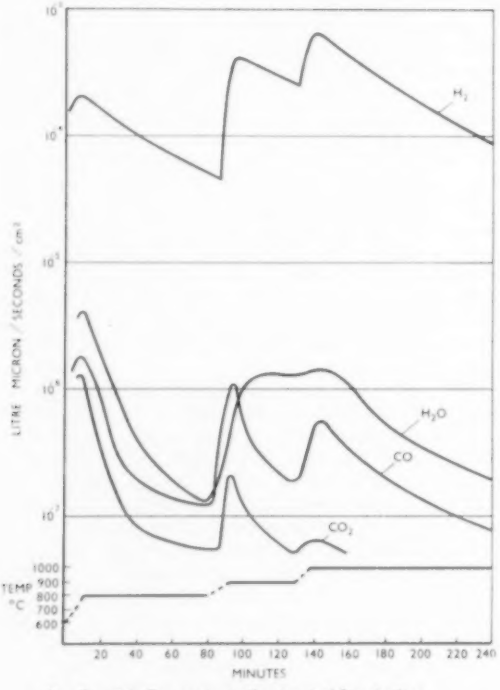
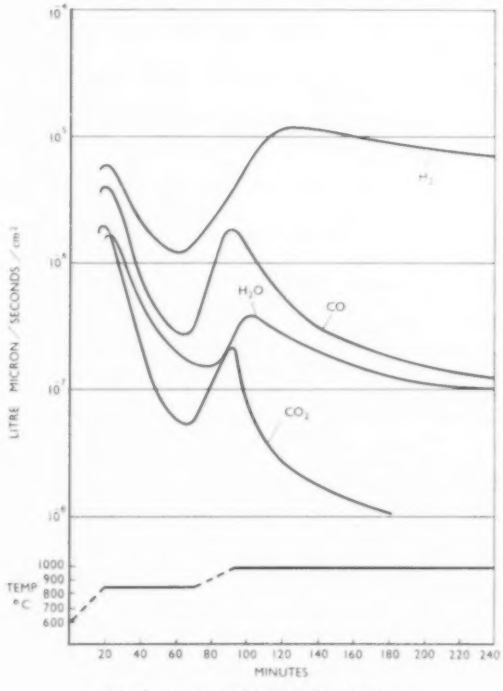


Fig. 2.—(a) Gas content of untreated fused silica.



(b) Gas content of treated fused silica.

advantage of high transparency to u.v. radiation when phosphor-coated jackets are used.

In recent years techniques have been developed for machine drawing fused-silica tubing. Tubing of excellent quality may now be made in all the sizes required, with very close dimensional tolerances and at substantially reduced cost compared with earlier methods of manufacture.

Unfortunately some of this machine-drawn tubing contains substantial quantites of gas, notably hydrogen, introduced during manufacture and difficult to remove quickly during lamp processing.

A study has been made of the gas content of one type of machine-drawn silica, using mass spectrometer techniques. Figs. 2(*a*) and 2(*b*) show the results obtained. The tubing, as drawn, fig. 2(*a*), contains a large amount of hydrogen which, however, can be substantially removed by baking for about one hour at 1100° C. Fig. 2(*b*) shows what happened when the specimen of silica degassed as shown in fig. 2(*a*) was exposed to the atmosphere for one hour. It is interesting as it indicates how quickly degassed silica can reabsorb substantial quantities of gas and water from the atmosphere. This absorbed material is surprisingly strongly bound to the silica.

It has been found that, by pre-baking silica tubing before lamp making, and by ensuring a minimum delay between pre-baking and lamp pumping, the process of lamp pumping is much simplified. Using a high-speed rotary pump it is possible to evacuate, bake, fill and seal-off a lamp body in less than six minutes.

A New Method for Applying Phosphors.

Most of the hpmv lamps made today have a phosphor-coated jacket surrounding the arc tube in order to improve the colour rendering properties or luminous efficiency. The phosphor is usually coated on to the glass jacket as a suspension in a solution of nitrocellulose and butyl acetate. Alternatively the dry phosphor may be dusted on to the glass surface previously coated with a thin film of some viscous solution such as potassium silicate in water. In both cases careful control of the process and materials is required and it is necessary to remove all traces of the binders before the lamp can be finally processed.

It has long been realized that electrostatic coating of phosphors avoids the difficulties of the methods mentioned above.

The technique is widely used for the precipitation of dusts of all kinds.[2] Typically, small particles of airborne dust are electrostatically charged and carried by the air stream into an electrostatic field where they follow the lines of force of the field, in a direction depending on the sense of their charge, and finally are precipitated on the electrodes of the field-producing system.

It is clear that a similar system might be used for precipitating a phosphor on to the walls of a glass vessel, provided that the glass to be coated can be made one electrode of an electric field system, and that the particles can be uniformly charged to the appropriate sign.

Attempts to coat phosphors in this manner have not been very successful for three main reasons:

(*a*) The adhesion of the particles to the glass has not been satisfactory.
(*b*) The phosphor particles have tended to aggregate.
(*c*) It has been necessary to heat the glass bulb to make it electrically conducting.

Fig. 3 shows diagrammatically an apparatus which appears to overcome all these difficulties and which has provided phosphor coatings, on a wide range of bulb sizes, which need no further treatment before final lamp processing.

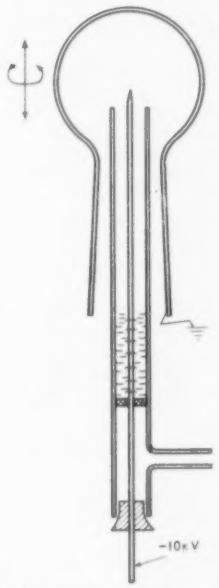


Fig. 3.—Electrostatic phosphor-coating apparatus.

The phosphor is conveyed into the bulb by a slow stream of air, the velocity of which is adjusted to carry up only single particles of phosphor. The stirring action of the air through the phosphor breaks down aggregates and provides a continuous supply of single particles. As the particles leave the tube they enter a region of corona discharge near the pointed electrode, which is maintained at −10 kV relative to earth potential. The charged particles are rapidly drawn to the inner surface of the glass bulb, which is covered with a thin film of water. This water film serves the double purpose of rendering the glass surface conducting and greatly improving the adhesion of the phosphor to the glass.

A bulb 90 mm in diameter can be coated with 0·7 grammes of phosphor in about 20 seconds. All that is required after coating is to dry the bulb for about 20 seconds with a stream of warm air.

The coatings produced with this apparatus are at least as satisfactory in all respects as the best coatings produced from nitrocellulose suspensions.

EXTENSION OF EXISTING LAMP RANGE.

A New Tungsten Filament Ballast Lamp.

It is well known that hpmv lamps can be operated in series with a tungsten filament which will replace the usual series choke and provide additional light, particularly in the red end of the spectrum where it is most needed. The filament may be mounted in the same bulb as the discharge lamp.

There are, however, serious limitations to the design of the filament as it has to withstand high current during the run-up period of the discharge and to have a life comparable with that of the discharge tube. If the filament is mounted in a phosphor-coated outer jacket there are difficulties in devising jacket pump schedules and gas fillings compatible with the requirements of both filament and phosphor.

Recent work on tungsten filament lamps has shown that it is possible to make lamps in very small fused-silica envelopes, provided a trace of iodine vapour is added to the normal gas filling.[3] The function of the iodine is to prevent blackening of the lamp envelope by evaporated tungsten, which would normally prohibit the use of very small envelopes.

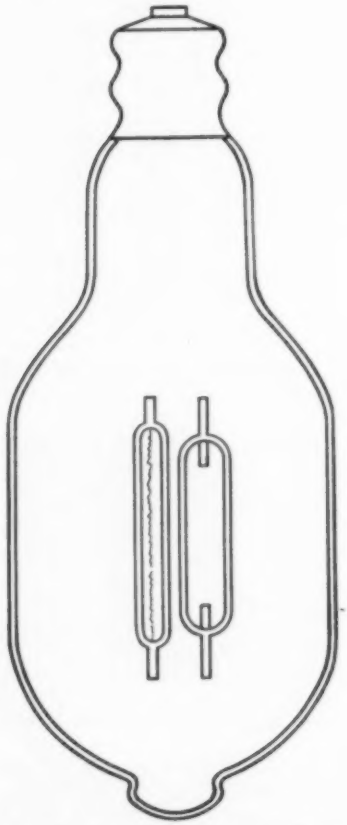


Fig. 4.—A new tungsten-filament-ballasted lamp.

It is possible to make an improved tungsten-ballasted, phosphor-coated hpmv lamp using these new iodine-filled tungsten filament lamps. Fig. 4 shows a lamp of 450 watts rating in which 200 watts and 250 watts are dissipated in the filament lamp and discharge tube respectively. It will be seen that the filament lamp is mounted close to the mercury lamp so that there is good mixing of the light from the two sources and rapid run-up is ensured by mutual heating.

Experimental lamps of this type in a phosphor-coated jacket have an efficiency of about 26 L/W, and a red ratio of about 11% for a life of 5000 hours.

A New Self-Contained Ballast.

In considering the design of self-ballasted lamps it is evident that, for highest luminous efficiencies, it is necessary to design for the highest possible ratio of discharge tube watts to ballast watts. This is still true of light-emitting ballasts of the tungsten filament type just described, because the luminous efficiency of the tungsten filament is much lower than that of discharge lamp.

Two difficulties arise in the attempt to increase the wattage ratio of the discharge component. The first is that the lamp becomes unstable and liable to extinguish if the voltage across the discharge is high compared with the voltage across the ballast in full operation; this effect becomes more marked as total wattage is reduced. The second difficulty is that a ballast designed for low wattage dissipation in full operation of the lamp will be very severely overloaded when the lamp is first switched on.

These difficulties are alleviated by a new form of ballast which does not itself produce a useful amount of radiation but enables the combination to work at improved luminous efficiency.

The stability of a ballasted hpmv lamp operating at a tube voltage V_T from some supply voltage V_m may be measured by the value $\triangle V_m$ by which the mains voltage may be decreased rapidly before the lamp extinguishes.[4] A value of $\triangle V_m > 0{\cdot}1 V_m$ is usually considered satisfactory in practice.

Fig. 5(*a*) shows the relation $\triangle V_m / V_m$ against V_T / V_m for a hpmv lamp of the following characteristics, burning horizontally on 50 c/s a.c. in series with a resistor:

Tube arc length	30 mm
Tube internal diameter	10 mm
Tube current in full operation	1·1 A

It will be seen that $\triangle V_m = 0{\cdot}1\ V_m$ when $V_T / V_m = 0{\cdot}41$, i.e. on a 220 volt supply V_T must not exceed 90 volts.

Fig 5(*b*) shows the same characteristic for a tube operating under similar conditions in series with a hot tungsten filament. It will be seen that, in this case, V_T may be increased to 97 volts. This improvement is due to the well known non-linear form of the volt-ampere characteristic of a hot tungsten filament.

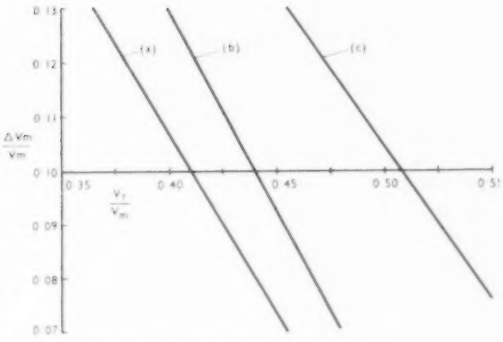


Fig. 5.—Effect of ballast on lamp stability.

By choosing the operating conditions of the tungsten filament, and disregarding the light output from it, it is possible to enhance this effect. Fig. 6 shows the volt-ampere characteristics of (*a*) a simple resistor; (*b*) a normal tungsten filament rated for 240 volts; (*c*) five uncoiled tungsten wires 0·02 mm diameter and 900 mm long connected in parallel and operating in 600 mm of argon. Fig. 5(*c*) shows the improvement in $\triangle V_m$ resulting from the use of a ballast with the characteristic shown in fig. 6(*c*). The maximum V_T for 220 V_m in this case is 110 volts for $\triangle V_m = 0{\cdot}1 V_m$.

This ballast assembly may be mounted in the same outer jacket as the discharge tube. It is advisable to use a number of filaments in parallel in order to reduce thermal capacity and ensure a rapid response. The filaments in this type of ballast run at a low temperature of about 700° C so that their life is very long. Furthermore, even in the lamp run-up condition, the filament is operating well below its maximum temperature.

This system has the disadvantage that no light is contributed by the filament. A simple calculation will show that the system described here is only marginally more efficient than conventional systems, but it is believed to be capable of improvement so that, with modern phosphor-coated lamps, a competitive low-wattage, self-ballasted lamp may result from further development of the principle.

Hot Tungsten Particles in the Discharge.

It may be of interest at this point to mention briefly work done on projecting clouds of fine tungsten particles into a hpmv discharge.

Tungsten powders varying in particle size from 1 to 20 microns have been dispersed in the arc of a hpmv discharge by mounting the discharge tube, containing up to 3 grammes of tungsten powder, on a vibrating table so that the particles were suspended in the discharge. The particles in the hot column of the discharge assume a temperature depending on their diameter. In the case of the smallest particles this temperature approaches that of the discharge column itself.

Several interesting phenomena may be observed in this experiment. It is possible to obtain some estimate of the temperature distribution in the arc and the part played by convection currents. The light from the discharge is strongly modified by the radiation from the hot particles and excitation of tungsten vapour.

A lamp of this type blackens very rapidly due to evaporated tungsten condensing on the tube walls; but it is perhaps worth considering the use of iodine vapour to overcome this, in the manner already described.

Luminous Efficiency of the HPMV Discharge.

For long-arc-length hpmv lamps, in which end effects can be neglected, the relation between wattage input and luminous output is of the very simple form shown by curve (*a*) in fig. 7. The luminous efficiency is given by the slope of (*b*) and it is clear that this will approach a maximum equal to the slope of (*a*) as the wattage input is increased.

The value of the intercept W_k is surprisingly constant at about 8 watts/cm of arc for a wide range of arc tube diameters and volts/cm. Elenbaas [5, 6] has equated this intercept to the wattage loss by thermal conduction from the hot discharge-column to the relatively cool tube wall, and has put forward arguments showing why this conduction should be substantially independent of arc operating conditions and arc tube diameter.

While this argument is sufficient to explain the behaviour of lamps of normal general lighting service design it does not appear adequate to account for the poor luminous efficiencies of lamps in which the arc-tube diameter is made much smaller than customary in these lamps. Since there is an obvious economic advantage in using narrow-bore silica tubing it is necessary to understand why it may not be used.

Curve (*a*) of fig. 7 gives lumen measurements on an experimental lamp of 50 cm arc length operating at 10 volts/cm in a silica tube of 25 mm internal diameter, while (*c*) shows the results for a lamp of 8 mm internal diameter operating under the same conditions. The

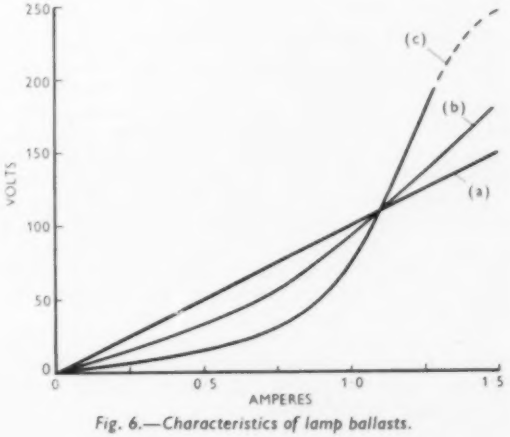


Fig. 6.—Characteristics of lamp ballasts.

luminous efficiency of the two lamps at, say, 25 watts/cm is 44 L/W and 32 L/W respectively.

The thermal conduction per unit length Q between two co-axial cylinders of radius a and b and temperature T_a and T_b in a medium of thermal conductivity κ is given by:

$$Q = \frac{2\pi\kappa(T_a - T_b)}{\log_e a/b} \quad \ldots (1)$$

For lamps of the type under consideration a can be defined as the radius of some isotherm outside the discharge column and b as the internal diameter of the discharge tube. Assuming κ and T_b constant then:

$$Q \propto \frac{1}{\log_e a/b} \quad \ldots (2)$$

Fig. 8 shows the relationship a/b against $-1/\log_e a/b$. In general lighting service hpmv lamps the ratio a/b is about 0·2 for $T_a = 5000°$ K.

$$-1/\log_e a/b \simeq Q' + S\,a/b \quad \ldots (3)$$

where Q' and S are constants.

The change in diameter of discharge columns with arc loading and tube diameter, and the change of κ with temperature are now being investigated in order to examine the possibility that the constant Q' in equation (3) is related to the intercept W_k.

NEW TYPES OF LAMP.

Whatever the outcome of this investigation, it has long been apparent to workers in this field that there is very little hope of improving the efficiency of hpmv lamps beyond the minor increases to be expected from improvements in techniques. It may, however, be pointed out that the high-pressure discharge is an efficient generator of radiation. Rössler[7] has shown for lamps of the type we are discussing that about 40% of the energy in the lamp is emitted at all wavelengths

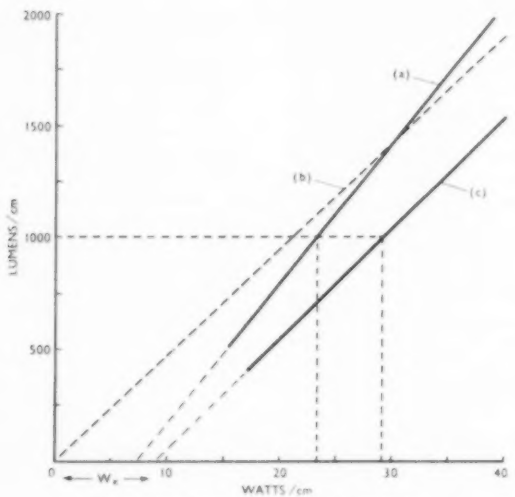


Fig. 7.—Luminous efficiency of hpmv lamps.

Referring again to fig. 7, if the heat loss in the 8 mm lamp is to be the same as in the 25 mm lamp the ratio a/b must remain constant. This means that the discharge radius in the smaller lamp must contract relative to that of the larger lamp in the ratio 8/25. This large decrease in a is not observed and it seems probable that the heat conduction losses are substantially greater in the small-bore lamp. A rough estimate of the increase in heat conduction necessary to account for the lower efficiency of the small bore lamp is obtained by selecting some lumen level such as 1000 lumens in fig. 7, which indicates that an extra loss of 5·5 watts/cm is required at that point.

Inspection of the curve in fig. 8 shows that, in the narrow range of a/b usually found in general lighting service lamps, the relation a/b against $-1/\log_e a/b$ is nearly linear and of the form

from the arc. The relatively small proportion of hpmv radiation in useful parts of the visible spectrum accounts for the relatively low luminous efficiency.

Since the high-pressure arc is an efficient generator of spectral radiation it is of great interest to consider what gases or vapours, other than mercury, might be used as light generators in this way. Many workers have experimented with the addition of cadmium, zinc, lead and similar metal vapours to the mercury discharge; generally with the intention of improving colour rendering properties. A particular study has been made of mercury-zinc vapour lamps in outer bulbs coated with magnesium germanate phosphor.[5] It has been shown that a lamp of 400 watt rating may be made with a luminous efficiency of about 40 L/W at 12% red ratio with excellent colour appearance and colour rendering properties.

However the life of such lamps is less than that of an ordinary mercury vapour lamp since the zinc rapidly darkens the silica tube wall. The cause of this attack is at present obscure as the density of zinc ions at the tube wall is extremely low; yet zinc vapour heated in a silica tube in the absence of a discharge has no effect on the silica, even after several thousand hours.

high efficiency of conversion into sodium radiation of thermal energy from the mercury vapour discharge.

The sodium line radiation in these mixed vapour discharges is strongly broadened towards longer wavelengths. The life of lamps of this type is extremely short, only a few minutes, owing to the very rapid attack of fused silica by hot sodium vapour.

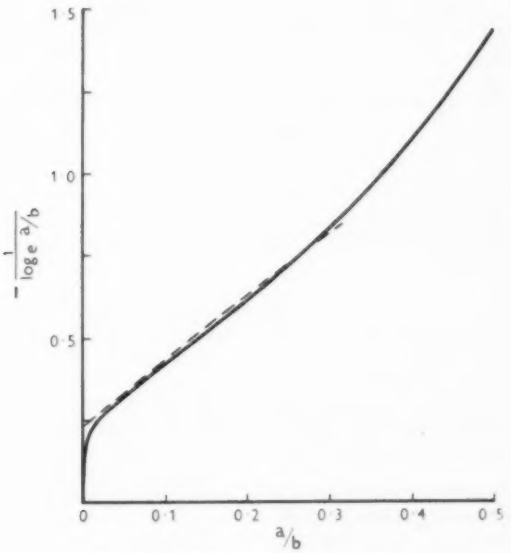


Fig. 8.—Heat conduction in hpmv lamps.

Extremely interesting experimental lamps may be made by adding low-excitation-potential alkali metal vapours to the mercury vapour discharge. Sodium vapour gives a typical result. At vapour pressures which are relatively low compared with the mercury vapour pressure in a lamp of normal 400 watt geometry in a silica tube, it is found that there is powerful excitation of sodium radiation which, combined with the mercury radiation, gives luminous efficiencies of the order 100 L W and much improved colour appearance compared with mercury alone.

It appears at present that the sodium vapour in an hpmv discharge plays little part in determining the electrical characteristics of the discharge, and that the sodium radiation is mainly from thermally excited sodium atoms in a sheath surrounding the mercury discharge, where the temperature is estimated to be about 4000° K. The high luminous efficiency of the mixed vapour discharge may be attributed to the

In spite of the very serious technical difficulties which appear at present to be associated with the manufacture of practical high-pressure discharge lamps with highly reactive vapours, it is believed that there is an important future for lamps of this type.

The most important task is the development of new envelope materials or techniques which will permit the development of high-pressure discharge lamps in vapours which are less volatile and more reactive than mercury vapour.[9]

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Generation and Amplification in the Millimetre Wave Field

By W. E. WILLSHAW, M.B.E., M.Sc.Tech., M.I.E.E.
(Hirst Research Centre).

This article, in which the author surveys the present position of generation and amplification at wavelengths down to 1 mm, is based on a lecture delivered before the Institution of Electrical Engineers on 25 January, 1961.

INTRODUCTION.

THE application of millimetre waves has been of growing interest since the work of Ryde, Van Vleck and others made clear the effect of water vapour and oxygen on the propagation characteristics of the atmosphere, and thus suggested which regions of the millimetre spectrum would be most valuable for different applications.

During the past fifteen years there has been emphasis in the use of millimetre waves for long-distance communication by waveguides. It seems very likely that the wavelengths required, as short as 5 mm or possibly shorter, will be generated, amplified and modulated by established types of microwave valves, particularly klystrons, backward-wave oscillators, travelling-wave tubes and special crystal diodes. However, continuous activity in spectroscopy, interest in the measurement of high-density plasma concentrations, and the realization of the significance of millimetre waves for the compact systems requirements of the space age have emphasized the need for power sources in the shorter millimetre wave region. This lecture is concerned with the present position of generation and amplification at wavelengths down to 1 mm. Since power sources generating energy simultaneously over a wide frequency spectrum do not generally permit sufficiently sensitive and accurate techniques of application, we shall concentrate particularly on narrow spectrum sources.

The field of amplification is not represented by any significant achievement. However, from the earliest days of microwaves, remarkable and continuing progress has been made with the aid of generators only, and it seems likely that once generation is practicable, amplification will follow as required. After all, most of the techniques available for generation are basically suitable for amplification.

In fig. 1 the atmospheric losses due to oxygen and water vapour at ground level are indicated. At sufficiently high altitude, reduction of partial pressures will, of course, reduce these to very low values. The total loss has a minimum in the region of 8 mm, a peak of nearly 20 dB/mile at 5 mm due to oxygen, and minima in the 3 mm, 2 mm and 1·5 mm regions. The effect of water vapour increases rapidly in going to 1 mm and below. The water vapour density in this case corresponds to a humidity of about 30% at ntp.

For contrast with later work, and as a reminder of the significance of millimetre waves in the earlier days of radio, fig. 2 shows the spark-gap generator produced in 1941 by Daunt and colleagues of the Clarendon Laboratory, Oxford.

A spark discharge takes place, through balls of lead shot carried by the oil film on the rotating wheel, being excited by the upper electrodes connected to an induction coil. Low-Q damped oscillations are radiated at the wavelength of 5·7 mm determined by the ball size, and a useful output power of the order of 5 mW is obtained.

PRINCIPLES OF ESTABLISHED DEVICES.

Turning now to devices capable of generating narrow-band energy we shall consider generation with established devices before discussing alternative approaches, recalling the physical ideas and concepts used in these. Two broad principles are used involving energy transformation from d.c. source to r.f. output power through the medium of an electron beam. These have been called 'O' and 'M' type, corresponding respectively to the use of the kinetic and the potential energy of the beam.

'O' Type Interaction.

In the 'O' type interaction shown in fig. 3 an electron beam is formed and accelerated, and then modulated as a result of passing through the r.f. fields of an input cavity. Electron bunches are formed gradually due to alternate acceleration and retardation in the cavity and subsequent drifting for a long enough time for fast electrons to catch up with slow ones. The

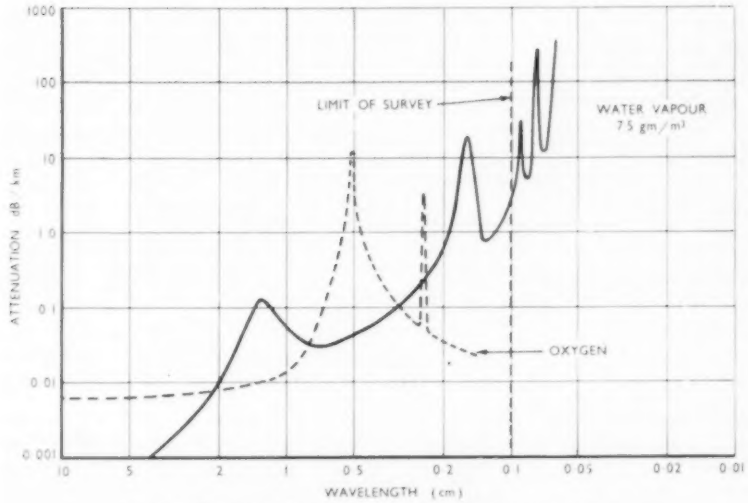

Fig. 1.—Absorption of microwaves by oxygen and water vapour.

See J. H. VAN VLECK, The absorption of microwaves by uncondensed water vapour, *Phys. Rev.*, **71**, p. 425, 1947.

bunches pass through the gap of the output cavity into which they induce power at the bunching frequency during the decelerating phase of the cavity field. Individual electrons are therefore slowed down and their kinetic energy removed. Assuming a beam voltage of 10 kV, the lengths of the gaps at both input and output need to be of the order of 1/20th of the output wavelength for efficient interaction, or 0·002 in. for 1 mm wavelength. Such a system is, of course, a klystron amplifier, and it may be made into an oscillator by suitable coupling of output and input resonators. Alternatively it may be made into an oscillator by reflecting back the bunched beam into the bunching cavity, resulting in a reflex klystron.

The travelling-wave tube represents another example of ' O ' type interaction, but in this case the process of bunching and energy extraction from the bunched beam is a continuous one. It now involves the use of a circuit, in this case a helix, carrying a wave travelling at a velocity just a little lower than the electron beam. The axial r.f. fields due to the travelling wave appear to be almost stationary when viewed by individual electrons, so that continuing energy exchange is possible. In particular, electrons in the positions where their motion is slowed down by these fields continue to give up energy to the wave along the whole interaction length. It turns out that the spacing between the elements necessary to produce the circuit needs to be about the same as the gap lengths in the klystron. In this case, however, this spacing of a few thousandth of an inch needs to be repeated accurately very many times.

From these examples of ' O ' type interaction it will be clear that the r.f. output power is derived from the kinetic energy of the d.c. electron beam; the initially accelerated beam is slowed down by the interaction process.

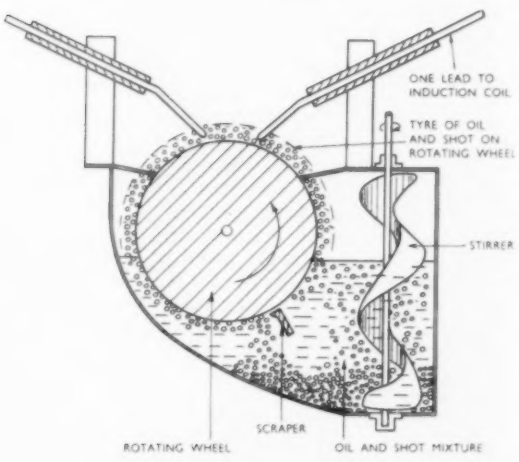

Fig. 2.—Short-wave (6 mm) spark generator.

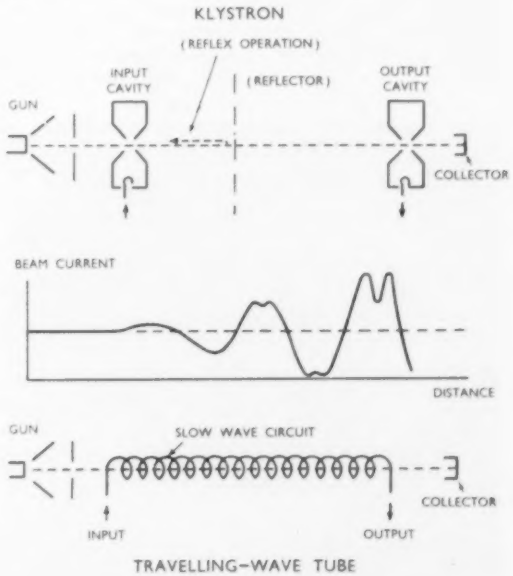

Fig. 3.—' O ' type interaction.

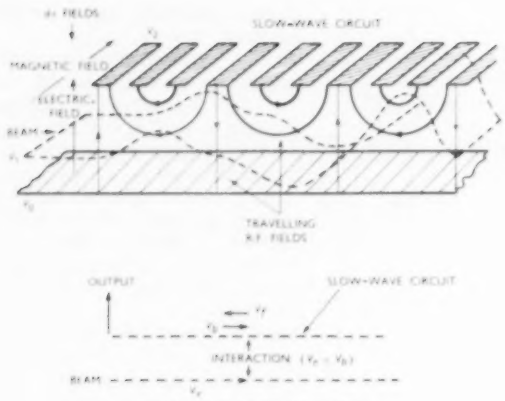

Fig. 4.—' M ' type interaction.

' M ' Type Interaction.

On the other hand the ' M ' type interaction process makes use of the potential energy of the electron beam, as shown in fig. 4. In this arrangement the beam is injected at relatively low velocity into a space in which both transverse electric and magnetic d.c. fields are present. The r.f. fields due to a suitable form of circuit are also present, travelling with a velocity close to that of the beam, and the electrons move steadily towards the circuit, or away from it, depending on their phase of entrance relative to the wave. Those moving towards the circuit, which is of much higher potential than the injection potential of the beam, absorb energy from the d.c. power source, which is transferred directly to the r.f. field, since the mean electron velocity does not change. Thus their potential energy is transferred to r.f. energy. Those moving away give energy to the d.c. power source and receive it from the r.f. field, but their effect is much smaller. The overall result is a considerable net energy transfer to the r.f. field.

So far as millimetre wave operation is concerned this principle has been made use of in the magnetron and in the ' M ' type backward-wave oscillator. In the magnetron the circuit is provided by a number of resonators, coupled together round the circumference of a circle, which produce an effective travelling wave of required velocity.

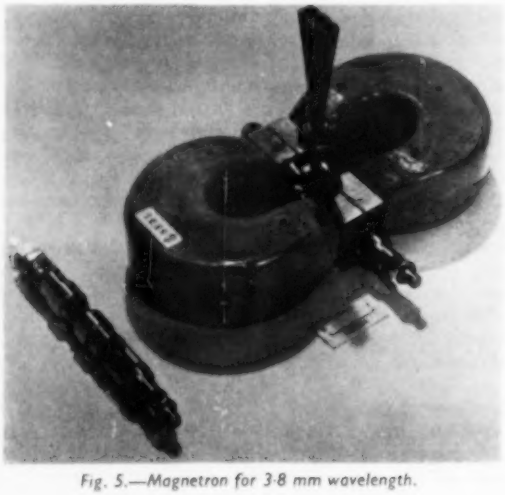

Fig. 5.—Magnetron for 3·8 mm wavelength.

Backward-Wave Interaction.

Finally we recall the principle of the backward-wave oscillator, which is applicable to any system involving energy exchange between an electron beam and the fields of a practical circuit.

The circuits necessary to produce waves of low enough velocity to allow effective interaction with an electron beam are of many forms, the helix and the periodically loaded waveguide being most common. They all have an effective waveguiding surface which has periodic changes in geometry and which cannot therefore produce a pure travelling wave. The complex wave produced can be thought of as due to an infinity of pure waves of different but inter-related velocities, travelling both in the direction of energy flow and in the opposite direction. In the backward-wave oscillator arrangement shown in fig. 4, the beam travels in the same direction as one of these component waves, which is opposite to the direction of energy flow, and interacts with it. The resulting r.f. energy builds up in the direction of energy flow and in particular modulates the beam injected into the system, thus providing a feedback mechanism for self-oscillation.

A characteristic of the backward-wave oscillator which is particularly important in the millimetre wave field is that the frequency generated is electrically

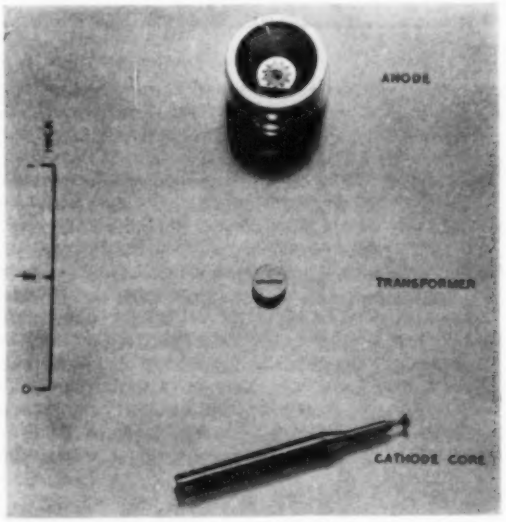

Fig. 6.—Components of magnetron for 3·8 mm wavelength.

tunable by variation of beam voltage. Thus frequency may be changed without displacement of mechanical components and without the inevitable complexity and circuit losses arising from this.

PERFORMANCE OF ESTABLISHED DEVICES.

In examining the performance of some of the established devices at millimetre wavelengths, we should bear in mind that where powers are quote for a given minimum wavelength, greater power may be achieved at longer wavelength by appropriate design.

MAGNETRONS.

Considering magnetrons first, fig. 5 shows a valve, operating at 3·8 mm wavelength, originally designed by the Services Electronics Research Laboratory and manufactured by E.M.I. Electronics Ltd. It has the small 18-circuit anode system shown in fig. 6, formed by hobbing, and operates under short pulse conditions with a magnetic field of 21 000 oersteds. It gives a mean output of 2 W and peak output of 5 kW with efficiency of 7%. Further reduction in wavelength may be obtained in principle by reduction of all significant dimensions. However, the magnetic field must at the same time be increased in inverse proportion to wavelength.

This requirement led to consideration some years ago of special conditions for the use of minimum magnetic field, and in 1955 my colleagues and I reported earlier work on the generation of c.w. power of 0·5 W at a wavelength of 5 mm using this low field approach, which also allows an increase of anode size, with a magnetic field of only 3600 oersteds. Following this the construction of an anode circuit for 1 mm wavelength was described, involving building up from 75 thin copper laminations brazed together, each of these being produced by electro-deposition on to a master prepared by photographic reproduction. Fig. 7 shows one of these laminations of 0·5 mm centre hole diameter, and it was possible to assemble these with good accuracy. Limited attempts at the time to mount the 0·15 mm diameter cathode accurately within such a structure were not satisfactory, but proposals aimed at avoiding this are indicated in fig. 8. An annular electron beam is injected into the anode system at one end with the angular velocity required for interaction with the resonator wave.

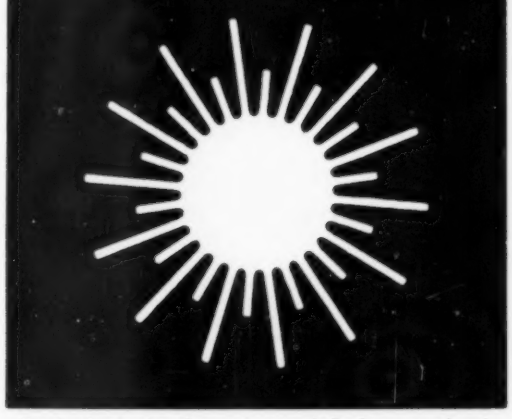

Fig. 7.—Lamination of magnetron anode for 1 mm wavelength.

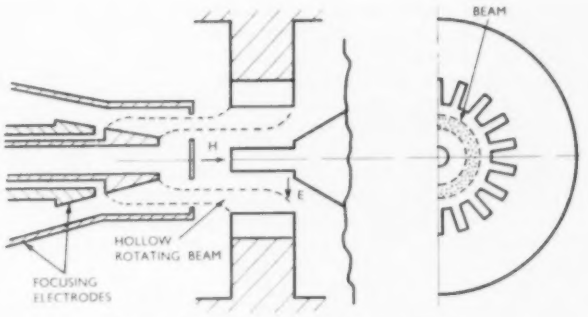

Fig. 8.—Proposed injection beam magnetron.

Operating in this ' low field ' region, with a magnetic field of 15 000 oersteds, Bernstein and Kroll reported a few years ago the generation of a wavelength of 2·5 mm, with a pulsed power output of 1-2 kW peak, mean power of a few tenths of a watt and efficiency of 1%.

KLYSTRONS.

Turning now to klystrons, Lafferty reported as far back as 1946 that a wavelength of 4·15 mm could be generated with a reflex klystron, difficulties in going to much shorter wavelengths being the need to provide sufficient cathode current density and the rise of the oscillation starting current due to circuit losses. A current tube of this kind developed by Messrs. Philips gives a power of the order of 150 mW at a voltage of 2500 V. Following this Van Iperen reported in 1959 the generation of 40 mW at 2·5 mm wavelength in a tube of the same basic design.

The design difficulties of klystrons may be minimized by self-excited harmonic generation, and a number of different arrangements have been proposed. Fig. 9 shows the 2-cavity klystron oscillator-multiplier developed by Elliott Bros. for the generation of 4 mm waves. The valve self-oscillates at a wavelength of 8 mm owing to interaction of the electron beam with the fields set up in the large cavity with drift tube. The beam, fully bunched at 8 mm wavelength, passes on to the small cavity resonant at 4 mm wavelength, and about 0·5 W of power can be taken out in a waveguide at this wavelength.

In an alternative arrangement, making the cavity of a reflex klystron resonant at the 29th harmonic as well as at the fundamental, Bernier and Leboutet reported in 1954 that a power of a few microwatts could be obtained at the wavelength of 1·7 mm.

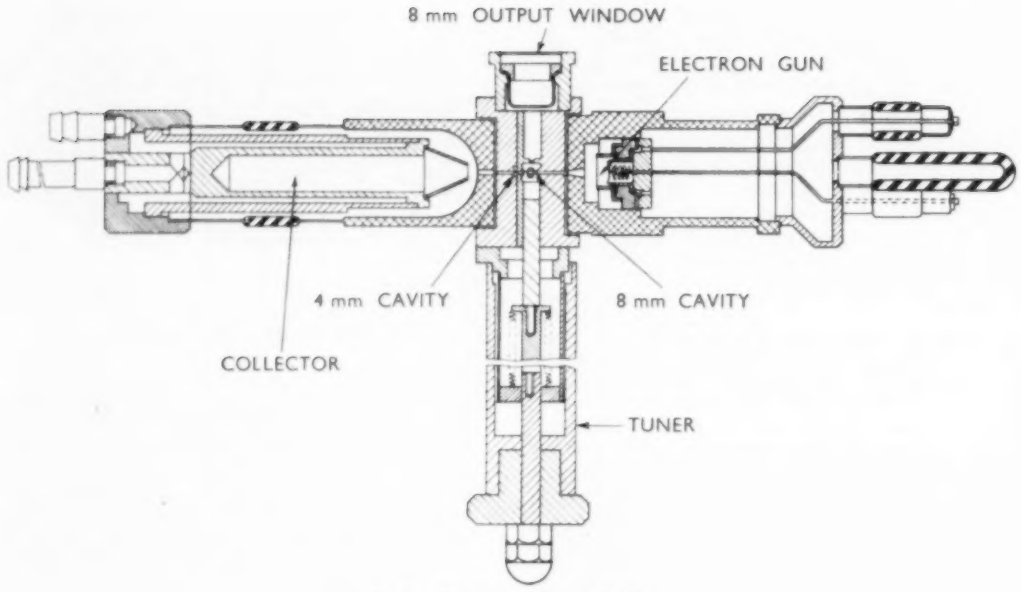

Fig. 9.—Klystron oscillator multiplier.

Backward-Wave Oscillators.

It is probably in the field of 'O' type backward-wave oscillators that the most spectacular advances have been made towards the shorter millimetre waves. In 1957 Karp, at Bell Telephone Laboratories, reported on a 1·5 mm oscillator giving a power of one milliwatt at a voltage of 2500 V. In this the circuit was of the ridge-loaded ladder type formed by winding a flat tape over a frame and brazing. Karp concluded that the inevitable circuit losses of this construction were likely to prevent further reduction in wavelength.

More recently work has been described by Convert, of Compagnie Generale de Telegraphie sans Fil in France, who is using a circuit of the slotted-cavity type to produce the shortest possible wavelength, since this is thermally very robust. Fig. 10 shows the general arrangement. The circuit or delay line forms with the surrounding enclosure a ridge waveguide, and is tapered at both ends to plain waveguides, one of which is connected externally through a thin glass window to the output load, the other in a similar way to a dummy load in which power reflected from the output end can be absorbed. The beam current passes along axial slots in the delay line. At wavelengths near 2 mm, powers greater than 50 mW have been generated with a tuning range of about 5% and a peak of 200 mW. In recent work on a model of this valve operating at 1 mm wavelength a power of 1 mW minimum has been obtained over a tuning range of at least 15%, up to 10 mW being produced at some wavelengths. This represents the most important achievement so far in the 1 mm region. The width of the slots used in the delay line is about 0·035 mm (i.e. just over 0·001 in.) and these are spaced by the same distance. It has been found possible to produce these with sufficient accuracy by using 'ordinary' milling methods.

One of the problems in the use of this type of oscillator is the attainment of a sufficiently tight coupling between the r.f. fields set up by the slow-wave circuits and the electron beam, without excessive interception of the current by the circuit. To avoid this an electrostatic focusing system is being tried out by my colleagues at Wembley, the arrangement being as shown in fig. 11. The beam passes into the space between the two parallel slotted delay lines operated at the anode potential of the electron gun. Outside the delay lines are focusing plates operated at, or near, the

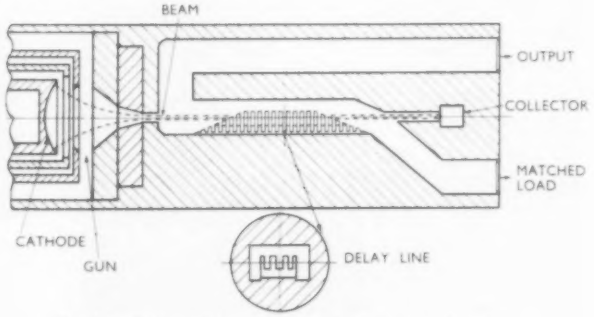

Fig. 10.—Backward-wave oscillator for 2 mm wavelength.

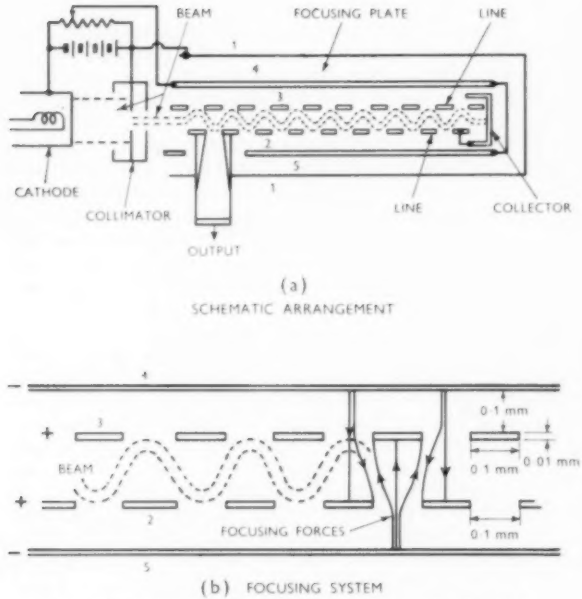

Fig. 11.—Electrostatically focused backward-wave oscillator for 2 mm wavelength.

cathode potential which set up the transverse focusing fields indicated. The beam passes automatically into the points of maximum r.f. coupling field in the gaps between the delay line bars.

Fig. 12 is an enlarged photograph of the molybdenum-sheet delay line used for a wavelength of 2 mm, and gives an idea of the accuracy that may be obtained. The line, which is 0·01 mm thick, contains 200 slots 0·1 mm wide and 0·9 mm long which are photo-etched on to it.

Fig. 12.—Molybdenum sheet delay line for electrostatically focused backward-wave oscillator

PASSIVE HARMONIC GENERATION.

A very large amount of work has been carried out over the years, particularly in the field of spectroscopy, by the use of harmonic generation methods. These have made use of silicon rectifiers as non-linear resistance harmonic generators.

Data obtained by Richardson and Riley show a power loss on 4th harmonic conversion to 3 mm wavelength of 30 dB, and other data suggest a further loss of 15 dB per harmonic. This necessitates very careful circuit work, but provided that powers around the microwatt level are usable, it provides a technique which with further advances in semiconductor diodes is likely to be of continuing interest at wavelengths in the millimetre region and below. Energy has in fact been generated and used at wavelengths as small as 0·5 mm, with the 18th harmonic of an 8·6 mm reflex klystron.

Fig. 13 shows the general arrangement of a typical multiplier system, the crystal being placed at the junction of fundamental and harmonic waveguides. Special crystal wafers are used with extremely short and fine whiskers, and good engineering design allows the fine mechanical adjustments required to be conveniently achieved.

The non-linear resistance harmonic generator is inherently of low efficiency, whereas a non-linear reactance harmonic generator can in principle have a high efficiency provided that suitable coupling circuits can be synthesized. Considerable effort is now being directed towards the design of low-loss semiconductor variable reactance diodes, and the use of these at centimetre wavelengths has already resulted

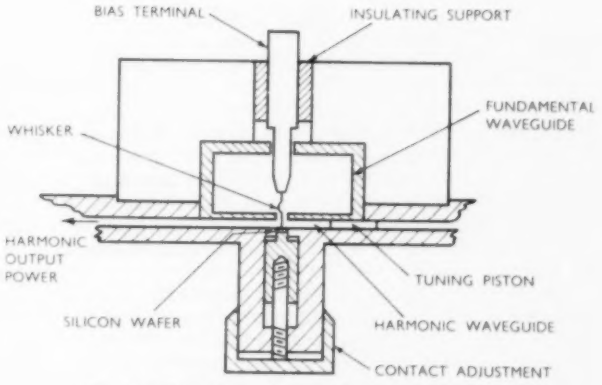

Fig. 13.—General arrangement of crystal multipler.

in more efficient harmonic generation. The circuit problems at millimetre wavelengths are, of course, formidable, since it is necessary for the circuit impedance in parallel with the diode to be high at all frequencies other than the fundamental and desired harmonic. Third harmonic generation to 3 mm wavelength using this technique has already been achieved by Leenor and Uhlir using silicon junction diodes, though no conversion figures are quoted. However, multiplication to 15 mm wavelength using the 60th harmonic shows a loss of only 35 dB.

One difficulty with semiconductor harmonic operation of this type is that power is limited by crystal

dissipation, so that low efficiency cannot be compensated for by increase of power input. Other forms of multiplier are not limited in this way. It has been demonstrated that suitable ferrites in a d.c. magnetic field have very effective frequency-doubling characteristics, and a power of 8 kW peak has been obtained at 15 mm wavelength with an efficiency of 25% by Melchor, Ayres and Vartanian.

The multiplying effect, which is obtained when the r.f. magnetic field due to the driving power is perpendicular to the d.c. magnetic field, arises from the fact that a double frequency component of r.f. magnetization is generated in the direction of the d.c. field. The arrangement used is shown in fig. 14. Pulse operation has been used so far; the prospects for c.w. operation do not appear to be so good with the best materials at present available.

More recently Ayres has demonstrated multiplying to a wavelength of 2 mm, using the ferrite arrangement of fig. 14(*b*). An estimated peak power of 50 W was obtained for one condition of operation and mean power of 0·5 mW for another. The input peak power was possibly a few tens of kilowatts.

Gas discharges have also been used to generate harmonic power at relatively high peak value. Following early experiments by Uenohara and colleagues, Baird has reported work in which a gas-discharge tube was placed across a junction between the waveguide carrying the exciting 3 cm power, and a waveguide carrying the harmonic power in an arrangement similar to the crystal harmonic generator just described. The discharge gas was wet air at a pressure of 10 mm. Harmonics of the order of 2-11 were excited giving a minimum wavelength of 3 mm with a peak power of about 30 mW. This robust simple system, which also makes use of pulse power, seems capable of much extension to shorter wavelengths.

An interesting approach to the use of the non-linear properties of an arc as a harmonic generator has been described by K. D. Froome of the National Physical Laboratory. The driving power of a few watts at 8·6 mm wavelength is passed along a waveguide filled with argon to a pressure of at least 20 atmospheres. One wall contains a small slab of calcium, and a d.c. arc less than 0·1 mm length is set up between this and a 0·5 mm diameter pointed tungsten wire placed parallel to the electric field. The harmonic power is coupled out by a suitable waveguide projecting through an E plane wall of the input guide close to the arc. Power at wavelengths down to 0·95 mm has been detected using a Golay infra-red detector as receiver, and it is estimated that with best adjustments an output of 1 microwatt may be obtained. This system has the merit of operating under c.w. conditions, and it is believe that further improvement in performance is possible with attention to detail.

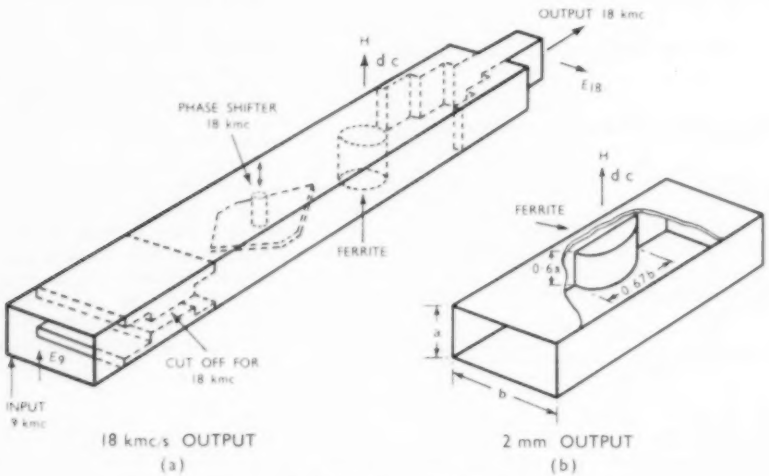

Fig. 14.—Ferrite frequency doublers.

ACTIVE HARMONIC GENERATION.

In addition to these methods of passive multiplication considerable attention has been applied to the possibility of using active multiplying arrangements, in which the non-linear characteristics of an electron beam may be made use of after modulation by a longer wavelength source.

It is well known that a travelling-wave tube is an effective multiplier. The design produced by Danielson, McDowell and Reed at Bell Telephone Laboratories for amplification at 6 mm wavelength (where it gives 200 mW of output power) is such that amplification down to 3 mm wavelength is likely. Multiplication from here to 1 mm then seems practical and the use of these tubes should result in an effective 1 mm generator provided that the delicate power matching and transfer problems can be overcome.

Incidentally B.T.L. are also planning a 1 W c.w. travelling-wave tube amplifier for 1 mm wavelength. In order to use a delay line of practicable size a beam voltage of 100 kV is being used with a current of a few milliamperes.

The effective generation of high-order harmonic power in beams is limited by space-charge debunching forces at beam voltages of the order of a thousand, and currents of tens of milliamperes. Work carried out by Coleman and Sirkis over the years has aimed to avoid this limit by the use of high-velocity beams, which also increases the output circuit size. In the arrangement shown in fig. 15 a beam is accelerated to a voltage of 20 kV and is then velocity-modulated at the frequency to be multiplied and allowed to drift and form bunches as in the klystron. The bunched beam enters an r.f. accelerating cavity also operated at the bunching frequency. The output beam, now increased in voltage to about 1 MV, has a very high harmonic content, with small velocity spread, and energy may be extracted in a suitable cavity resonant at the harmonic frequency. The shortest wavelength detected is reported to have been 3·14 mm, the 34th harmonic. At 8·3 mm wavelength a power of 90 W peak has been obtained.

One difficulty experienced in using this technique has been that of providing a suitable cavity for coupling the harmonic power to a circuit. This is a common problem in the shorter millimetre-wave field, and recently proposals have been made to use the Cerenkov effect to overcome this.

When an electron travels through or close to a dielectric medium at a velocity greater than the velocity of light in the medium it radiates energy. The radiation occurs at a characteristic angle θ to the electron trajectory, so that cos θ is the velocity ratio.

For a random succession of electrons, the successive radiation waves represent a continuous spectrum of incoherent radiation over a frequency range limited only by the dispersive properties of the medium. The range is that for which the electron velocity exceeds the velocity of light in the medium. To give coherent power at a single frequency and its harmonics the beam needs to be bunched, and recently Coleman and Enderly have combined the powerful harmonic bunching techniques just described with the use of this Cerenkov coupling effect to produce a generator of the type shown in fig. 16. Harmonic power is radiated from the beam at the characteristic angle into a specially designed dielectric prism, being then internally reflected to appear as a plane polarized t e.m. wave in space from which it is received by a tapered horn and transferred to normal coaxial line detecting equipment. Preliminary results so far with the 13th harmonic suggest good correlation between theory and experiment, a mean power of 0·3 W being measured at 8 mm wavelength, and it is thought that powers of the order of 1-5 W should be obtainable in the submillimetre wave range. This approach is particularly interesting in demonstrating a form of coupling to a bunched beam which does not depend on the use of intricate circuits.

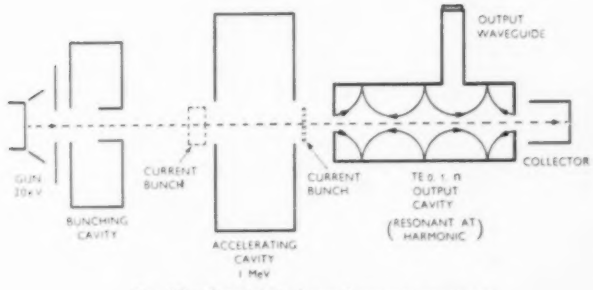

Fig. 15.—Relativistic beam harmonic generator.

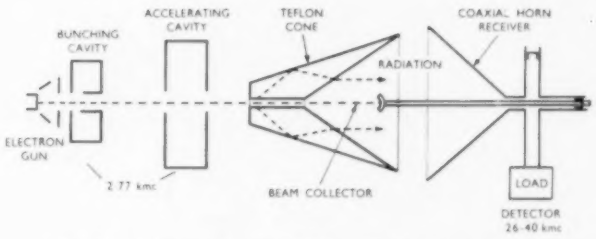

Fig. 16.—Relativistic beam multiplier with Cerenkov coupler.

USE OF DOPPLER SHIFT.

Another approach to the problem of producing short millimetre waves is the use of the technique of doppler shift. The frequency of the radiation observed from an electron oscillating in space at frequency f_1, may be increased by simultaneous translation of the electron at velocity v to $f_2=f_1/1-\beta \cos \theta$ where θ is the angle between the electron trajectory and the line joining it to the observer, $\beta=v/c$. It will be seen that by making the electron velocity high enough f_2 can be made much greater than f_1 on the beam axis where $\theta=0$.

In the undulator described by Motz, the oscillation of the electron is achieved by passing the beam through a series of transverse magnetic fields which alternate periodically with distance, as shown in fig. 17. With magnet spacing of 5 cm and velocity ratio 0·989 (corresponding to a beam voltage of 3 MV), radiation of wavelength 0·5 mm will then be generated on the axis at $\theta=0$ by individual electrons.

To achieve effective radiation from a stream of electrons, these need to be bunched over lengths comparable with the output wavelength generated. However, in spite of the lack of deliberate bunching, Motz estimated that in one experiment a peak power of the order of 1 W was generated with a beam voltage of 2 MV. A number of other proposals for the use of doppler shift between fast electron beams and r.f. waves have been made, but as far as is known they have not yet been taken to the point of producing power.

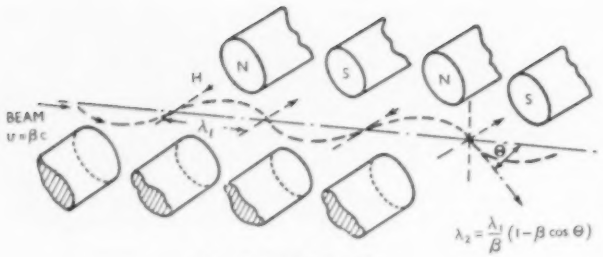

Fig. 17.—The undulator.

magnetic field, the latter being indicated in fig. 18(*d*), which shows the essentials of a form of oscillator which has been used to generate a few watts in the 15 mm wavelength region. It uses the simplest form of circuit: a plain parallel line. In this illustration the form of the trajectories of electrons which lose energy is indicated, from which it can be seen that, in principle, the whole of the r.f. energy of the electrons which resides in the energy of rotation may be transferred to r.f. output power by interaction with the transmission line field. Those electrons which begin to gain energy from the field are rapidly removed at the bottom negative electrode.

A fundamental requirement of this kind of oscillator, or indeed of any kind which uses directly the phenomenon of cyclotron resonance, is that of a magnetic field which is inversely proportional to wavelength and which is as high as 100 000 oersteds for 1 mm wavelength. With present techniques this involves a bulky magnet but it need not provide a limitation.

An entirely different way of using periodic beam motion shown in (*e*) involves interaction with the r.f. field of a fast-wave system such as a surface wave, over the region of transverse variation of field intensity. The periodic motion set up in the way just described, or by a suitable electric potential distribution, takes the beam in and out of the strong field region with the result that the required difference in energy exchange between favourable and unfavourable electrons may be achieved. Futhermore harmonic operation is possible since the beam may spend one or more periods of the oscillation in the weak field region before re-entering the strong field region.

When considering the usefulness of these newer methods of power generation involving the use of periodic beams we must bear in mind that they bring

PERIODIC BEAM SYSTEMS.

One aim of the methods of generation just described is the avoidance of the very tiny slow-wave structures involved in the use of the more customary beam-wave interaction processes covered earlier. In these processes the injected beam is smooth and the circuit is periodic, and much consideration is being given to the possibility of using a circuit which is smooth (i.e. a plain waveguide) and a beam which is periodic instead.

Beam periodicity can be produced and used in a number of ways. In the anti-klystron suggested by Chernov in the U.S.S.R. and shown in fig. 18, a beam is used in which the electron trajectories are circles, centrifugal force being balanced by a radial electric force, and electrons pass through fields set up in a gap coupling to a normal waveguide. The beam rotation frequency and therefore the wavelength of amplification or generation is determined by the steady electric focusing field.

A simple way of producing beam periodicity is by the use of a steady magnetic field. An electron injected into a magnetic field acquires an angular frequency ω_c called the cyclotron frequency. If a transverse r.f. field is present of frequency equal to the cyclotron frequency, the orbit radius increases or decreases with time depending on phase of entry, corresponding to a gain or loss of energy. If the wave, of frequency ω now moves with velocity v_p and the electrons drift with velocity v_e in the direction of movement of the wave, the condition for maximum interaction is modified and includes a doppler shift term, becoming

$$\omega = \omega_c \left(1 - \frac{v_e}{v_p}\right)$$

Thus the frequency of maximum interaction may be changed both by magnetic field (ω_c) and by electron drift velocity (v_e). The electron motion may be either parallel or perpendicular to

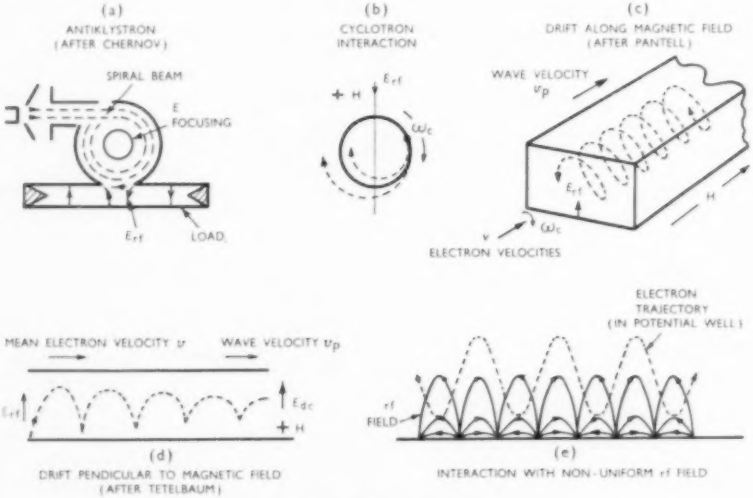

Fig. 18.—Periodic beam systems.

with them new problems of high magnetic and high electric fields, but they do hold out hope of providing valves with simple circuit systems for the shortest wavelengths.

APPLICATION OF FIELD EMISSION.

An aspect of design common to all the systems of generation described so far is that they need high electron emission density and high electric field. The properties of electron field emission which have been of research interest for many years fit in well with these requirements. In field emission, electrons are dragged from the surface of a cold metal by the application of high electric fields, and study in the U.S.A. over the years by Dyke and his colleagues has shown the conditions for good performance and life. A life of 1000 hours with no change of performance may be obtained with a d.c. emission current density of 10^7 A/cm^2, with a total current of 7 mA and operating voltage of 4·5 kV. To achieve good performance very low residual gas pressure is required, of the order of 10^{-9} to 10^{-12} mm mercury, but developments in high-vacuum techniques are rapidly making this practicable. The electric field at the cathode surface is in the region of 5×10^7 V/cm, and by controlled electropolishing of the emitting point, useful controlled emission may be obtained over the range 320 V to 500 000 V. High total current may be achieved by the use of a number of points, a beam power of 1 kW being obtained with 10 points.

MASERS AND TUNNEL DIODES.

Finally we consider the possibility of using techniques involving the characteristic resonance and emission properties of gases and solids, as in the maser. So far the outlook for the wavelength range under discussion does not appear too promising; at much shorter wavelengths it could be quite different.

In a proposal made by Singer for a tunable oscillator or amplifier, a beam of atoms having a net magnetic moment is used, for example a heavy alkali metal. Atoms of upper and lower energy levels are spatially separated by passing the beam through a non-uniform magnetic field. The upper-state atoms travel on and enter a cavity in which there is a uniform magnetic field, where transitions from the upper energy level to the lower occur, at a frequency determined by the magnetic field. By using a sufficiently high field and a sufficiently small cavity it should be possible to obtain amplification down to millimetre wavelengths. With present knowledge it is thought that the limit of the method might be 5 mm, set by cavity limitations.

Using a four-level ruby maser Momo, Myers and Foner have been able to generate oscillations of a few milliwatts peak at around 4 mm wavelength. Using a 2·4 cm oscillator with a steady magnetic field of 2500 oersteds, the populations of two energy states are saturated. The magnetic field is then pulsed up to 29 000 oersteds, when radiation is observed at wavelengths at which the solid ruby cavity is resonant, as a result of the consequent change of energy difference between the lower excited levels and an unexcited level. By the use of increased magnetic field further reduction in wavelength should be possible.

The use of the more familiar c.w. pumped solid-state maser offers advantages over the arrangements described above, but in its simplest form this requires a pump wavelength less than that of the millimetre wave signal. The maser has, however, the property that there is no need for the pump signal to be coherent. With this in mind, recent results with optical pumping will be watched with interest. So far, of course, the maximum wavelength reached is well below 1 mm.

The tunnel (Esaki) diode has the property of behaving as a very low negative resistance over a wide frequency range, although the associated shunt capacitance is high. It has been possible to obtain low power oscillations in the 3 mm region with one of the diodes incorporated in an appropriate cavity, and it seems likely that with further work, a reduction in this wavelength will be possible.

PRESENT OUTLOOK.

Future activity at wavelengths down to 1 mm is likely to depend heavily on techniques of generation and amplification not unlike those now well established at longer wavelengths. This opinion does not arise through any conservative desire to extend the known art (those in close contact with the field are only too aware of the problems) but simply because more attractive techniques have not yet been proposed. The task of finding alternatives is rendered particularly difficult by the high degree of sophistication required even at wavelengths of the order of 5 mm, particularly in spectrum coherence, in order to achieve high overall system efficiency and size.

Consequently any new approach must be competitive on this basis, and a method involving the use of high-energy electrons, for example, with its consequent high-voltage-supply problems, will not replace existing approaches involving watch-making methods if it cannot compete on power, efficiency, overall convenience, and so on. After all, as it has been pointed out elsewhere, watch-making techniques are commonplace in at least one industry!

It is however necessary to select those aspects of existing approaches which hold out most hope of easing the problems set by small components, especially in the direction of power dissipation limitation. For this reason there is likely to be increasing interest in systems which involve the interaction of periodic electron beams with fast-wave circuits. On the other hand slow-wave systems may still be used if alternative wave-slowing means can be devised. For example, the use of an appropriate ionized-gas filling for the waveguide with magnetic field is one approach which is attracting considerable research effort at the present time.

TECHNICAL LITERATURE

A digest of recent articles and papers by members of the G.E.C. and its associated companies

TEMPERATURE SCANNING AND LOGGING EQUIPMENT (959).*

By A. C. Blay, F. C. Flint and P. G. Davy (Applied Electronics Laboratories, Stanmore).

The Transactions of the Society of Instrument Technology, **13**, 2, *June* 1961.

A description is given of an equipment designed for automatic scanning and logging of the outputs of 900 thermocouples installed in the reactor core of a nuclear generating station. The design includes a particularly flexible system of scanning. In the case of each measurement alarm-level comparisons are made and a difference value is calculated. Outputs are provided on two strip printers, an electric typewriter and a tape punch. The equipment is intended for almost continuous operation, so that great emphasis has been attached to the need for reliability.

VISUAL PROBLEMS ON MOTORWAYS.

By J. M. Waldram (Central Research Laboratories, Hirst Research Centre).

Transactions of the Illuminating Engineering Society, **26**, 2, *pp.* 66-78, 1961.

The visual problems of drivers on the motorway have been studied by new techniques and compared with the problems on traffic routes, with special reference to the possible need for fixed lighting. By day the visual problems are generally much less severe on the motorways, but the vehicle and the driver have less in hand to cope with emergencies and consequences of an accident are often more grave. By night the information presented to the driver by headlights, reflector studs, rear-lights and signals are found to be inadequate and often confusing. Fixed lighting of good quality has been shown to be capable of giving the driver all the information he needs, and it is concluded that a technical case for its installation can be made out. The accident rate on motorways is low at present traffic density, but on motorways abroad where the density is greater high accident rates occurred which have been substantially lowered by the installation of fixed lighting. Technical characteristics for fixed lighting on the motorway are derived from the observed requirements. The paper does not discuss questions of engineering, economics or policy. Some suggestions for guidance and visual signalling on the motorway are discussed in an appendix

AN EXPERIMENTAL COLOUR TV RECEIVER: SETTING UP AND ADJUSTMENT.

By E. Ribchester (Hirst Research Centre).

The Journal of the Television Society, **9**, *pp.* 137-145, *Oct.-Dec.* 1959.

The purpose of this paper is to discuss the experience which has been gained in developing and using several experimental receivers. All these receivers have used the R.C.A. shadow mask tube and have been of the same general kind, but most of the experience gained applies to other types of receiver, operating on the British version of the N.T.S.C. system.

MECHANICAL DESIGN DETAILS OF 4 ft by 3 ft WORKING-SECTION LEG (BEDFORD WIND TUNNEL).

By A. L. Baxter (Engineering Group, Erith).

The Engineer, **211**, 5489, *pp.* 546-548, *April* 7, 1961.

The 4 ft by 3 ft wind tunnel at R.A.E. Bedford is eventually to incorporate a variable nozzle which is now under construction: the problems posed by the severe and varying temperature and pressure gradients on this assembly and their proposed solutions are explained. Unusual mechanical details elsewhere in the working-section leg are also described here.

ACHIEVING MACH 5 TEST FLOW.

By E. P. von Bergen (Hirst Research Centre).

The Electrical Times, **139**, 18, *p.* 703, *May* 4, 1961.

This article describes in detail the operation of the electrical servo systems employed to control the movable jacking stations which determine the shape of the flexible plate nozzle and supersonic diffuser of the Bedford Mach 5 wind tunnel.

SOME ACOUSTIC AND PSYCHOLOGICAL ASPECTS OF MULTICHANNEL SOUND SYSTEMS.

By D. M. Leakey (Hirst Research Centre).

Journal of the British Sound Recording Association, **6**, 5, *pp.* 118-125, *May* 1960.

The article describes briefly a theory, based on directional hearing, which aims to account for the observed phenomena associated with multichannel sound systems. It satisfies two criteria:

(*a*) It is mathematically and logically reasonable.

(*b*) It is in good agreement with the practical results obtained during an extensive period of controlled experiments using objective methods of measurement.

Notice that it is in good agreement with the observed results as measured by objective tests; it does not necessarily agree with subjective impression. Subjective impressions can be very misleading, but it must never be forgotten that it is subjective impression that finally counts in the assessment of a practical sound system.

PRACTICAL ASPECTS OF SINTERING TUNGSTEN AND MOLYBDENUM.

By D. J. Jones (Hirst Research Centre).

Journal of the Less-Common Metals, **2**, 2-4, *p.* 76-85, 1960.

Manufacturing procedures for the preparation of tungsten and molybdenum powders together with the method of pressing the powders in a mould and direct sintering the pressed bars at high temperatures are given. A description is given of the method of sintering, in particular, molybdenum in a hydrogen-water vapour atmosphere at about 1750° C and of the continuous pressing, partial sintering and casting technique developed to meet demands for relatively large size plate and sheet.

Brief reference is made to the preparation of alloys by sintering in the presence of a liquid phase and of pseudo alloys by the infiltration technique.

HIGH-POWER TRANSMITTING VALVES WITH THORIATED FILAMENTS FOR USE IN BROADCASTING.

By H. S. Walker, W. H. Aldous, R. G. Roach, J. B. Webb and F. D. Goodchild (Hirst Research Centre).

The Proceedings of the Institution of Electrical Engineers, **107**, *Part B*, 32, *March* 1960.

A major change that has occurred in high-power transmitting valves during the last decade is the introduction of the thoriated tungsten filament or cathode. The paper describes the technology of these cathodes and some of the valve characteristics resulting from the change-over from a pure tungsten cathode. Details are given of the various properties of thoriated tungsten cathodes resulting from the carburization process which is necessary to give stable emission. The performance is given of six typical types of transmitting valves used both in the sound and television services of the B.B.C. These are typical of many other types of large valves with thoriated cathodes which differ only in minor aspects from those described. Detailed performance results are given, together with a study of the economies of thoriated cathodes in practice. In considering the installation of these valves in place of the valves using bright tungsten cathodes, consideration has been given to the economic aspects of installation. Illustrations of the six types of valves described in the paper and survivor curves both for tungsten and thoriated tungsten valves are given, together with the curves showing loss of programme due to valve failure.

It seems clear from the results that not only do thoriated tungsten filaments or cathodes give economy in operation, but the lives in many cases are considerably extended.

THERMO-ELECTRIC COOLING.

By N. L. Harris (Hirst Research Centre).

Electrical Review, **167**, 10, *pp.* 383-386, 2 *September* 1960.

Semiconductor materials have electrical properties which lie between those of metals and those of insulators. Their most familiar use is in the germanium and silicon transistors and diodes which are being used in ever-increasing numbers not only to replace thermionic valves but also to do many things which valves could never accomplish. This article deals with the thermo-electric cooling properties of semiconductors, the principles underlying which were established in the classical physics of the early nineteenth century. Until recently no practical developments were forthcoming but workers in the field of solid-state physics have demonstrated that thermo-electric cooling offers distinct possibilities for the future.

THE APPLICATION OF PHOSPHORS IN LIGHTING.

By A. H. McKeag (Hirst Research Centre).

Transactions of the Illuminating Engineering Society, **25**, 2, *pp.* 41-52, 1960.

Research in phosphors for use in the lighting field has been pursued continuously over a period of nearly thirty years. Sulphide phosphors were already established on a manufacturing basis at the beginning of this period and the principles governing their preparation were well understood. The main problem was to develop a similar range of phosphors responsive to short u.v. radiation which would be applicable to the low-pressure mercury vapour discharge lamp. A few phosphors based on the luminscent minerals, such as Willemite and Scheelite, had been prepared previously but with relatively low efficiencies. During the intervening years the range of available phosphors has been considerably extended and some of the more important developments are listed. The halophosphate phosphors were discovered in this country in 1942 and quickly superseded the zinc beryllium silicate and magnesium tungstate combination, used to provide white colours in the early fluorescent tubes. They are now used throughout the world for high efficiency fluorescent tubes.

EXPLICIT FORM OF F.M. DISTORTION PRODUCTS WITH WHITE-NOISE MODULATION [EXTENSION AND CORRECTION].

By R. G. Medhurst and J. H. Roberts (Hirst Research Centre).

The Proceedings of the Institution of Electrical Engineers, **107**, *Part C*, 12, *September* 1960.

Monograph No. 352 presented formulae for the distortion/signal ratio in the top channel of a trunk radio system employing f.d.m. frequency modulation when the signal passes through a transmission network whose characteristics (amplitude and/or phase) are non-linear with frequency. The formulae apply when the amplitude and phase characteristics are expressed as power series in frequency (measured from the carrier frequency). This information is important for the design of amplifiers and demodulators.

The formulae given covered amplifier phase characteristics and discriminator amplitude characteristics up to sixth degree; amplifier amplitude characteristics and discriminator phase characteristics were, however, covered only up to fourth degree, which will not be adequate for many purposes. The data required to fill this gap have now been evaluated using the methods already described in the Monograph.

INTERNAL FRICTION IN SYNTHETIC QUARTZ.

By C. S. Brown (Hirst Research Centre).

Proceedings of the Physical Society, **75**, *p.* 459, 1960.

The hydrothermal growth of large crystals of quartz, of a quality suitable for piezoelectric application, has been described by Brown *et al.* (1952), Hale (1952) and Walker and Buehler (1954). The properties of conventional oscillator crystal units cut from synthetic quartz have been measured (Brown and Thomas 1957, Bechmann 1955), and found to be closely similar to those made from natural quartz in all respects, including *Q*-factor.

However, conventional quartz crystal units are insensitive to changes in the intrinsic damping in the material, the changes largely being masked by the extraneous losses imposed by the mounting system. It is now possible, using a special design of crystal unit described by Warner (1952), to reduce extraneous losses to a very low level and so obtain a measure of the internal friction in the quartz.

DEPENDENCE ON TEMPERATURE OF THE INTER-LAYER SPACING IN CARBONS OF DIFFERENT GRAPHITIC PERFECTION.

By E. G. Steward, B. P. Cook and E. A. Kellett (Hirst Research Centre).

Nature, **187**, 4742, *pp.* 1015-1016, *September* 17, 1960.

In a previous communication, attention was directed to important inconsistencies and gaps in the literature concerning thermal expansion in graphitic carbons perpendicular to the hexagonal layer-planes. Preliminary experiments were reported and, while these clarified the picture to some extent, the need for further experiments at higher (above 1200° C) and lower (below 20° C) temperatures was indicated. Special diffractometer techniques required for these measurements have now been developed and will be described elsewhere: meanwhile, the extended results are reported.

SEEING AND LIGHTING IN STREETS.

By W. R. Stevens (Central Research Laboratories, Hirst Research Centre).

Proceedings of the Norwegian Traffic Engineering Conference at The Technical University of Norway, Trondheim, 5-11 *January* 1961.

Although present street lighting techniques are based on well-established principles, the standard of lighting needs generally to be raised to keep down the accident rate and to make the use of roads more efficient. New road surfaces are increasing the difficulties of street lighting, and new research—

for example, studies of driving—is showing more clearly the requirements. A basis for good practice for main road lighting is suggested. For side roads the problem is different and one solution is given based on a recent experiment.

A multiplicity of columns in a street is unattractive. While no method of street lighting without columns is universally satisfactory, some techniques worth considering in special circumstances are described.

LIFE CHARACTERISTICS OF SOME TYPICAL SEMICONDUCTOR DEVICES.

By R. Brewer and D. J. E. Richards (Central Research Laboratories, Hirst Research Centre).

Journal of the British Institution of Radio Engineers, **21**, 6, *pp.* 485-489, *June* 1961.

Evidence from life tests of transistors is presented as an indication to equipment designers of the changes in electrical characteristics which may occur during the use of these devices. The effects of physical tests such as those for storage at high and low temperatures, high humidity, vibration and shock are also reviewed, and an indication is given of the incidence of inoperative failures. Operational reports of some equipments using large numbers of semiconductor devices are compared with laboratory life test evidence.

THE FORMATION AND STRUCTURE OF DELTA ALUMINA.

By H. P. Rooksby (Hirst Research Centre) and C. J. M. Rooymans (Philips Research Laboratories, Eindhoven, Netherlands.)

Clay Minerals Bulletin, **4**, 25, 1961.

Delta alumina is a transition form obtained during the conversion of boehmite to corundum. Alternative methods have been found for preparing this alumina in a well crystallized condition, enabling detailed X-ray powder data to be compiled. The X-ray data are accounted for by a large tetragonal structure cell of which the axial ratio is 1·47, or 3/2 times the axial ratio of the spinel-like pseudo-cell of Saalfeld. The lattice parameters are $a_0 = 7{\cdot}96$ Å and $c_0 = 11{\cdot}70$Å. This large cell provides an integral number of vacancies, contrasting with the 2⅔ vacancies of the pseudo-cell, and allows the atomic arrangement to be ordered.

SYNTHETIC GEMSTONES.

By E. A. D. White (Central Research Laboratories, Hirst Research Centre).

Reprinted from The Chemical Society Quarterly Reviews, **15**, 1, 1961.

The aims of gem synthesis are two-fold. From the scientific viewpoint it is desirable to produce large single crystals of good quality; as gems the products should be indistinguishable from natural stones, that is, they should contain imperfections of the same type as natural crystals. The latter aspect has largely been ignored by workers in this field, although in certain instances synthetic stones resemble the natural counterparts very closely. This is usually true when the crystallization process used closely parallels a natural geochemical process, as for example, in hydrothermal growth.

This paper is concerned with the production of good-quality crystals which are, perhaps, more perfect than the natural counterparts. However, in one respect the synthetic gemstones cannot compete with natural material; this is in their sheer size and the scale of their growth conditions.

VELOCITY DISTRIBUTION IN ELECTRON STREAMS.

By P. A. Lindsay (Hirst Research Centre).

Advances in Electronics and Electron Physics, **13**, *Academic Press Inc., New York*, 1960.

The main object of this article is to review the work which has been done in the past in calculating the velocity spread in the flow of an electron stream. Furthermore, the article aims at clarifying the general problem of velocity distribution by presenting a concise method for deriving the effects which a velocity spread must have both on the surrounding field and on the electron stream itself. The method of approach adopted is based exclusively on the powerful concept of electron density in a six-dimensional space composed of configuration and momentum spaces joined together. It will be assumed in this that the electrons can be represented by a smooth cloud of charge—thus the local interactions among individual electrons will be entirely neglected in the treatment adopted. This simplifying assumption seems to be fully justified on purely physical grounds, the interaction between individual electrons and their time of flight being generally small.

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